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CORNING GLASS WORKS

TECHNICAL STAFFS DIVISION

IMPROVED SCREEN
FOR
REAR PROJECTION VIEWERS

PHASE II. THEORETICAL STUDIES

April 26, 1966

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ABSTRACT: This constitutes the final report of the second phase of the government sponsored program, "Improved Screens for Rear Projection Viewers". It summarizes six months of theoretical investigations relating to the scattering of light by rear projection screens. These investigations have been conducted toward determining the relations between viewing properties and such physical characteristics as particle diameter, their number density, and the relative index of refraction between the scattering particles and the surrounding medium. The results of this study have been used as specific materials requirements for samples of the glass ceramics, Fotoform and the sintered glasses.

The results of a study on the feasibility of using hollow optical fibers with metallic coatings is given along with a discussion of preliminary models of two dissimilar, novel, rear projection screens.

The last section discusses the instrumentation for testing samples of rear projection screens.

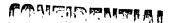
KEY WORDS: Rear View Screen, Projection Screens, Light Scattering, Hollow Fibers, Instrumentation

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ABSTRACT

The analytical relations between the viewing properties of rear projection screens and such physical characteristics of the screens as particle diameter, number density, and the particle's index of refraction relative to the surrounding medium have been theoretically investigated. We have shown how each of these parameters influences the scattering of light by the screen material, and subsequently how they determine the uniformity of screen brightness, efficiency, and color fidelity. Specific material requirements for the next phase of this program have been generated using the results of this study.

Other approaches which do not depend upon light scattering by a volume of material are also being investigated. The feasibility of using hollow glass fibers with metallic coatings is given along with a description of preliminary models of a louvered screen and an ultraviolet sensitive screen.

Lastly, a goniophotometer to measure the light scattering properties and a modulation transfer function analyzer to measure the resolution of samples made of Corning Glass Works' materials are described.

CONFIDENTIAL

I. <u>Introduction</u>

This constitutes the final report concluding the second phase of the government-sponsored program, "Improved Screens for Rear Projection Viewers." The main objective of this program is the fabrication of improved rear projection screens from available Corning Glass Works' materials.

This report summarizes the theoretical investigations relating to light scattering by rear projection screens. The conclusions of this study are presented in Section II. The major conclusion is that optimum rear projection screens, for most applications, can be obtained by properly choosing the correct size, number density, and relative index of refraction of the scattering particles.

A background to the problems associated with rear projection systems is given in Section III. Projection and viewing problems, some terminology, and constraints introduced by the screen are presented. The behavior of a typical rear projection screen is illustrated as well as how the light scattering property of the screen material determines the viewing properties. Finally, the influence of factors such as magnification, projection and viewing distances, screen size, optics of the projector, and the ambient light level are discussed.

The results of the Mie theory of light scattering are covered in detail in Section IV. The equations based on this theory were used to compute light scattering functions for particles of different size and different relative indices of refraction. These scattering functions are given in Appendix A. Additional modification of these angular scattering functions was required because of total internal reflection and refraction at the air glass interface of the screen. The corrected data are given in Appendix B. From these data, parameters such as efficiency and axial gain are correlated with particle size.

Additional data are presented to illustrate how the particle size influences the amount of light trapped through total internal reflection, how this degrades image contrast, and how this influences the sensitivity of the material to ambient light. The influence of particle size and refractive index on the color fidelity of a material is covered in detail. Specific material requirements are formulated to give a rear projection screen material that theoretically meets the contract requirements. This section is concluded with a brief discussion of Rayleigh scattering and why materials consisting of particles much smaller than the wavelength of illumination are unsuitable for use in rear projection screens.

Alternate approaches directed toward other types of rear projection screens and screen materials are discussed in Section V. The difficulty of using metallized, hollow glass tubes is outlined and substantiated by experimental data. Optical design and applications of ultraviolet sensitive screens and louvered screens are also included.

Section VI is devoted to a description of the instrumentation to be used in evaluating samples of Corning Glass Works' materials. Each of the five main sections of the goniophotometer, which measures the angular scattering properties, is discussed. The principles of operation of the modulation transfer function analyzer, and the details of making the special sine-wave resolution target are then covered.

Three appendices follow which present the raw computer data, the converted data, and a list of the three programs used to compute the light scattering functions and perform the necessary modifications discussed in Section IV.

II. Conclusion

1. An analysis of the computer data indicates that the angular gain functions of particles with identical sizes but different refractive indices are similar. The axial gain (θ = 0) differs at most by 5 percent at α = 5 and by only 15 percent at α = 10. The major difference being for M = ∞ , which represents highly reflective particles.

The most obvious difference between the scattering functions corrected for refraction at the air glass interface and those which have not been corrected is that the former are somewhat broader.

The contract requirements for uniformity of screen brightness and efficiency are met by particles in the size range $1.75 \le \alpha \le 2.25$, where α is the ratio of the particles' circumference to the wavelength of illumination inside the medium. This dictates a particle diameter from .2 to .3 micron. Thus it can be expected that on axis these screens can only be from 3.0 to 3.5 times brighter than a uniformly diffusing screen.

The efficiency of the screens is strongly influenced by the particle size. For a value of α greater than 2.0,2, losses through backscattering are insignificant compared to those produced by total internal reflections. Losses through internal reflections become negligible beyond $\alpha = 4$, except for reflecting metallic particles. The major factor limiting the use of large particles is the resulting non-uniformity of the screen. Thus the low efficiency materials are the most sensitive to ambient light.

The refractive index of the particles is relatively unimportant in determining the shape of the scattering

function, but strongly influences the color characteristics. The further the relative refractive index is from unity, the better the color fidelity of the material.

An expression relating the reduction of contrast in an image to the fraction of light internally trapped in a material has been derived. It shows that if half of the trapped light eventually passes through to the viewers, the reduction of contrast is linear with the fraction of light trapped.

Rayleigh scattering theory has been considered and the general scattering function investigated. Separate terms in the scattering function have been individually considered and numerically evaluated to understand better how they contribute to the scattering function. We have been able to show theoretically that rear projection screens made from Rayleigh scattering materials are unsatisfactory for a number of reasons. First, although their scattering functions are very broad and uniform, these screens are inefficient and have low brightness gains. Second, the resolution of such screens is correspondingly very low. the strong wavelength dependence of the scattering function and scattering cross section impose nearly impossible constraints which, when not met, result in screens which have very poor color characteristics. Applications for these materials probably lie only in low gain, low resolution, monochromatic screens.

III. Background of the Problem

The function of a rear projection screen is to accept an image from a projector on one side and present it to viewers on the other. To do this it must diffuse and re-radiate the incident illumination. The types of projectors in use range from television screens to conventional slide projectors. The effectiveness of such a display system is governed by the light scattering characteristics of the screen and by the geometries under which it is illuminated and viewed. The scattering properties of various screen materials have been discussed in a number of good articles 1-7.

The viewing properties of rear projection screens are determined by their light diffusing characteristics and also by internal reflection and absorption. The behavior of a typical rear projection screen is illustrated in Figure 1. Two rays of light are shown incident on the screen, one at point A, the other at B.

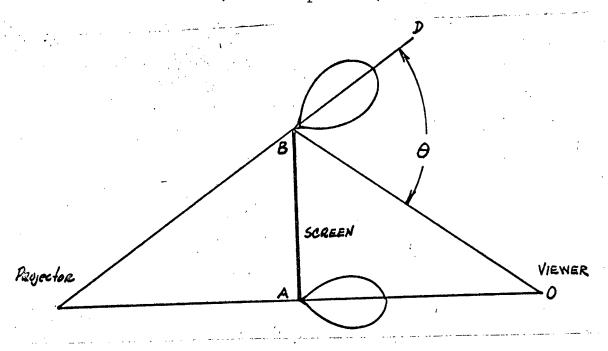


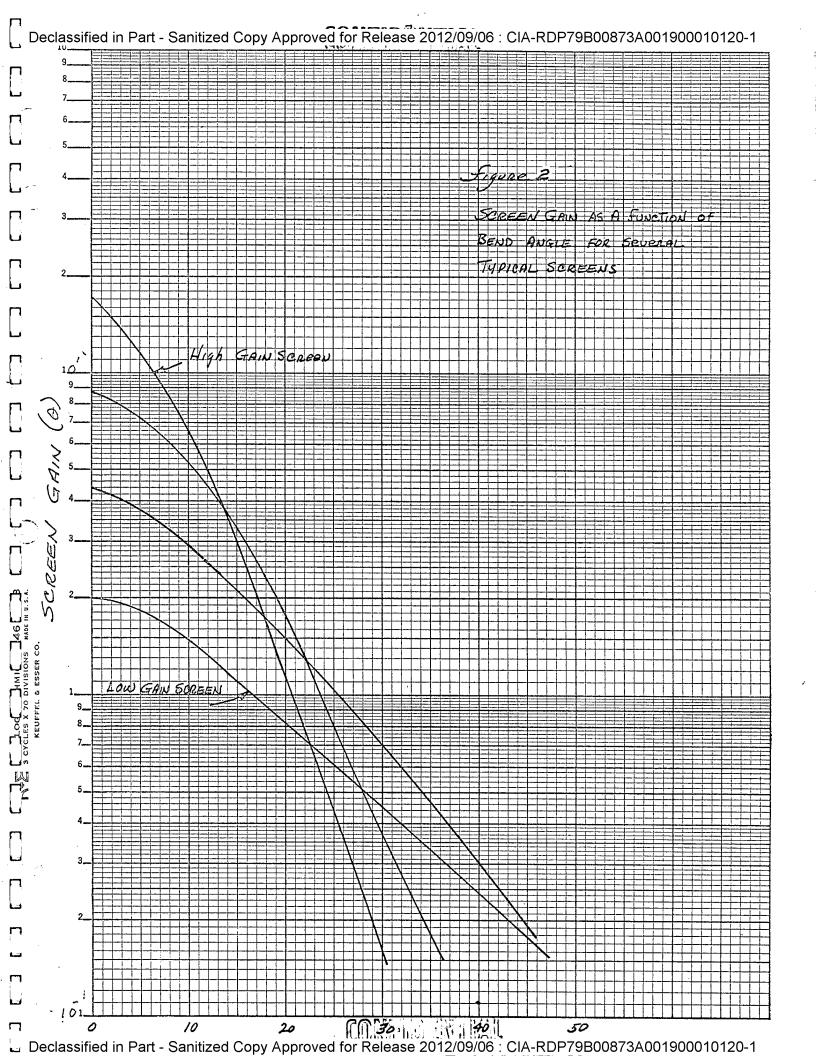
Figure 1. Typical Rear Projection Screen Geometry

Continuation of the line representing the incident ray through a point at the screen establishes the principal axis for that ray. The scattering function for that point on the screen also has its axis colinear with this principle axis. An observer at 0 will view point A along its principle axis, but he will view point B at some angle off-axis. The intensity of point B is determined by the angle DBO, at which the scattering function must be evaluated. This angle, θ , termed the "bend angle," is a function of the size of the screen and the projection and viewing distances.

The scattering function of any material is obtained by measuring, with a goniophotometer or comparable instrument, the brightness of a narrow, parallel beam of light as it is spread out by the screen. These intensities are then normalized to a reference taken to be a perfect isotropic diffusor where the intensity of the scattered light is uniform and independent of the angle θ . These data are called gain curves.

Screens which do not diffuse as uniformly as the isotropic screen will appear brighter over a certain range of viewing angles. The angular gain curve will have a value greater than unity in this region. Because a diffusing screen is a passive element which does not add energy to the light passing through it, any increase in gain above unity for one viewing position must necessarily result in a gain less than unity at some other position, Figure 2. It is important to note that viewing requirements generally call for greater viewing angles in the horizontal plane than in the vertical direction. This necessitates a screen which is anisotropic, i. e., the gain curve should be broad for the horizontal plane and relatively narrow for the vertical plane.

The intensity ratio between the light incident on the transparency and the screen is equal to the inverse square



of the magnification. Thus, if the screen can be made half as big, it will require only a fourth as much power to illuminate, and the bend angles will be considerably smaller. The closer the screen is to the audience, the larger are the bend angles; hence, the difficulty of maintaining a uniform picture increases. The wider the screen also has a comparable effect. the screen, the greater the range of bend angles; hence, the problem of projecting an acceptable picture is also more difficult. Bend angles are increased by using short focal length projection lenses placed closer to the screen, or by increasing the f/No. at which the projection lens is operating. The faster the lens, the more light can be projected on the screen; however, this also increases the bend angle and may require a lower-gain screen to maintain sufficient uniformity of illumination. It is important to note that the screen may be brighter overall for an observer at the center of the audience than for one near the edge. It has been found, however, that it is more important to view a uniformly illuminated image than a brighter non-uniform picture. In any case, brightness must be sufficient for all to view the display with comfort.

IV. Theoretical Investigations

A. Mie Scattering

1. Theory

The light scattering characteristics of the materials to be investigated are given by the Mie theory of light scattering. This theory is founded on the general solution to the boundary value problem of an isolated sphere in an electromagnetic field. Although this theory is very general, it finds primary application when the size of the particle is about the same size or larger than the wavelength of the incident radiation.

The important equations derived by Mie for both polarizations of the scattered light are

$$I_{\parallel} (\theta) = \left[\sum_{n=1}^{\infty} \{ A_n \pi_n + B_n [\mathbf{x} \pi_n - (1 - \mathbf{x}^2) \pi_n'] \} \right], (1)$$

$$I_{\perp}(\theta) = \left[\sum_{n=1}^{\infty} \left\{A_{n}[\mathbf{x}\pi_{n} - (1 - \mathbf{x}^{2})\pi_{n}'] + B_{n}\pi_{n}\right\}\right], \qquad (2)$$
where π_{n} and π_{n}' are the first and second derivatives, witherespect to \mathbf{x} , of the legendre polynomials $P_{n}(\mathbf{x})$ of order n-with \mathbf{x} and

$$A_{n} = \left[\frac{(-1)^{n+\frac{1}{2}}(2n+1)}{n(n+1)}\right] \left[\frac{s_{n}(\alpha)\frac{ds_{n}(\beta)}{d\beta} - M*s_{n}(\beta)\frac{ds_{n}(\alpha)}{d\alpha}}{\phi_{n}(\alpha)\frac{ds_{n}(\beta)}{d\beta} - M*s_{n}(\beta)\frac{d\phi_{n}(\alpha)}{d\alpha}}\right], (3)$$

$$B_{n} = \left[\frac{(-1)^{n+3/2}(2n+1)}{n(n+1)}\right] \left[\frac{M^{*}S_{n}(\alpha) \frac{dS_{n}(\beta)}{d\beta} - S_{n}(\beta) \frac{dS_{n}(\alpha)}{d\alpha}}{M^{*}\phi_{n}(\alpha) \frac{dS_{n}(\beta)}{d\beta} - S_{n}(\beta) \frac{d\phi_{n}(\alpha)}{d\alpha}}\right], \quad (4)$$

where
$$S_n(\alpha)$$
 = Riccati Bessel function = $(\frac{\pi\alpha}{2})^{\frac{1}{2}}$, $J_{n+\frac{1}{2}}(\alpha)$, $\phi_n(\alpha)$ = Riccati Hankel function =

$$S_n(\alpha)$$
 + j $(-1)^n \left(\frac{\pi\alpha}{2}\right)^{\frac{1}{2}} J_{-n-\frac{1}{2}}(\alpha)$, and $J_{n+\frac{1}{2}}(\alpha)$ and $J_{-n-\frac{1}{2}}(\alpha)$ = Bessel functions of half integral order.

Thus, the only physical parameters are:

The angle θ , between the direction of propagation of the light scattered and the direction of the incident light, Figure 3,

$$\alpha = \frac{\pi D}{\lambda} , \qquad (5)$$

and

$$M^*\alpha = \alpha (M - ik)$$
 (6)

where D = diameter of spherical particle

λ = wavelength of incident radiation in surrounding media

M = index of refraction of particle
 relative to surrounding media

k = extinction coefficient of the
 particle material

 $i = \sqrt{-1}$.

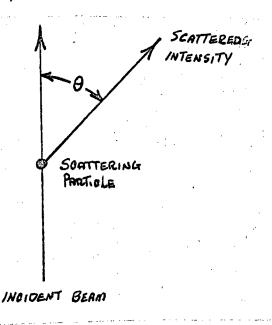


Figure 3. Scattering Geometry

To solve any given scattering problem requires tables of the real and imaginary parts of A_n and B_n , tables of the Legendre polynomials and their first and second derivatives $^{10-14}$. These are then combined using a desk calculator or preferably a large digital computer into values of I (θ) and I (θ) from which the angular distribution function "I(θ)" is obtained

$$"I(\theta)" = \frac{I_{\parallel}(\theta) + I_{\perp}(\theta)}{2\pi\alpha K} \qquad (7)$$

where the scattering coefficient, i. e., the ratio of the scattering cross section to the geometrical cross section is,

$$K = \frac{2}{\alpha^2} \cdot \sum_{n=1}^{\infty} \frac{n^2(n+1)^2}{2n+1} (|A_n|^2 + |B_n|^2).$$
 (8)

Hartel¹⁵ suggested that Equations (1) and (2) could be simplified in form by the repeated use of recurrence relationships between the derivatives and products of Legendre polynomials. Recently Chu and Churchill succeeded in rearranging of radiation scattered by nonabsorbing spheres in terms of a series of Legendre polynomials¹⁶,

"I
$$(\theta)$$
" = $\frac{1}{4\pi} \sum_{n=0}^{\infty} a_n(\alpha_n \beta) P_n(\cos \theta) = \frac{1}{4\pi} + \frac{1}{4\pi} \sum_{n=1}^{\infty} a_n P_n(\cos \theta),$
(9)

where the coefficients $a_n^{},$ are functions of α and $\beta\,,$ but not of the angle, and are given by

$$a_{n} = \frac{(2)(-1)^{n}}{\alpha^{2}K(\alpha,\beta)} \sum_{j=1}^{\infty} \sum_{k=1}^{j} (\frac{2}{1+\delta jk}) \{ (2n+1) \}$$
 (10)

$$\left[\frac{j(j+1) + k(k+1) - n(n+1)}{2}\right]^2 W_{jkn}W_{jk}^+ V_{jkn}V_{jk}^{}$$

where

$$\delta_{jk} = \begin{cases} 0 & \text{for } j \neq k \\ 1 & \text{for } j = k \end{cases}$$
 (11)

$$W_{jk} = Re(A_j) \cdot Re(A_k) + Im(A_j) \cdot Im(A_k) + Re(B_j) \cdot Re(B_k) + Im(B_j) \cdot Im(B_k) , \quad (12)$$

$$V_{jk} = Re(A_j) \cdot Re(B_k) + Im(A_j) \cdot Im(B_k) + Re(B_j) \cdot Re(A_k) +$$

$$Im(B_j) \cdot Im(A_k), \qquad (13)$$

$$W_{jkn} = 0$$
, if $j + k - n \neq 2r$, $r = 0,1,2...k$, (14)

$$W_{jkn} = \frac{(\angle j + n - k) (\angle k + n - j) (\angle j + k - n) (\angle \frac{j + k + n}{2})^{2}}{(\angle j + k + n + 1) [(\angle \frac{j + n - k}{2}) (\angle \frac{k + n - j}{2}) (\angle \frac{j + k - n}{2})]^{2}}, (15)$$

x > 30 false x = xx, x = 0, 2, 2...

$$V_{jkn} = 0$$
, if $j + k - n \neq 2r + 1$, $r = 0,1,2...k(16)$

and

$$V_{jkn} = \frac{(2n+1)(j+k-n)(j+n-k+1)(k+n-j+1)(\angle j+n-k+1)(\angle k+n-j+1)(\angle j+k-n-1)(\angle \frac{j+k+n+1}{2})^{2}}{4(\angle j+k+n+1)[(\angle \frac{j+n-k+1}{2}) \cdot (\angle \frac{k+n-j+1}{2})(\angle \frac{j+k-n-1}{2})]^{2}}$$

if
$$j+k-n = 2r + 1$$
, $r = 0,1,2...k$, (17)

where Im = Imaginary part,

Re = Real part,

\$\angle\$ = Factorial.

COMPRENTIAL

The advantage of expressing the angular distribution of intensity in the form of Equation (9) rather than Equations (1) and (2) is obvious. The intensity at any angle for which the Legendre polynomials are available can be computed from a set of coefficients for a given α and M. general, the number of significant terms in the series is about equal to 2α . The Legendre polynomials are available at one-degree intervals, and their behavior is better known; interpolation with respect to θ can be done more accurately than with $I_{ii}(\theta)$, $I_{ii}(\theta)$, " $I(\theta)$ ", or the tabulated derivatives of the polynomials. Interpolation with respect to α and β is also easier with the coefficients a_n , than with I_{II} (heta), I_{\perp} (heta), or "I(heta)", and need be carried out but once for all angles.

Additional advantages of the representation of the angular distribution of scattered radiation by Equation (9) can be noted. The power scattered into any region, and particularly into the forward and backward hemisphere, can be obtained by simple analytical integration. By assuming that a particle receives power only from adjacent particles having the same multiple-scattering distributions, Hartel developed the following equation in terms of the same coefficients a_n , for the angular distribution of the k-th scattered radiation in a dense dispersion:

$$"I_{k}(\theta)" = \frac{1}{4\pi} [1 + \sum_{n=1}^{\infty} {\frac{a_{n}^{k}}{(2n+1)^{k-1}}} P_{n} (\cos \theta)] \cdot (18)$$

It is somewhat simpler to evaluate (9) than Equations (1) and (2), because only values of A_n and P_n (cos θ) are required and are easily available. However, the tables of a_n and P_n (cos θ) are very limited,

while the tables of A_n and B_n are by far more complete, i. e., they have finer divisions of α and M and cover a larger range of particle sizes. For these reasons, Equations (1) and (2) were used for the single scattering investigations. The angular coefficients approach will be utilized if a study of multiple scattering is necessary.

2. Mie Scattering Theory Applied to Rear Projection Screens

The screen must not only diffuse the incident illumination but do it efficiently as well. The efficiency EFF(M,α), is defined as the ratio of the scattered light I_s , forming the image which passes through the screen, to that incident I_o , thus,

EFF(M,
$$\alpha$$
) = $\frac{2\pi}{L_{\odot}} \int_{0}^{\pi/2} I(M, \alpha, \theta) \sin \theta d\theta$

where I is given by

$$I_{o} = 2.2\pi \int_{0}^{\pi} I(M,\alpha,\theta) \sin \theta \ d\theta$$
 (19)

The angular gain of a scattering material is defined as the ratio of intensity of the light scattered at a given angle by any given material to that scattered by an isotropic radiator.

Let $I(\theta)$ and $I_i(\theta)$ be the angular scattering functions for an experimental sample of material and an isotropic material respectively, and let $I'(\theta)$ and $I_i'(\theta)$ be the angular scattering functions normalized to the respective incident intensities

$$I'(M,\alpha,\theta) = \frac{I(M,\alpha,\theta)}{2\pi \int_{0}^{\pi} I(M,\alpha\theta) \sin \theta d\theta} , \qquad (20)$$

$$I_{i}'(M,\alpha,\theta) = \frac{I_{i}(M,\alpha,\theta)}{2\pi \int_{0}^{\pi} I(M,\alpha,\theta) \sin \theta \, d\theta}$$
 (21)

Since the one diffuser is isotropic, we know that $I_{i}(\theta) = C_{i}$; hence, (21) becomes

$$I_{i}'(M,\alpha\theta) = \frac{C_{i}}{4\pi C_{i}} = \frac{1}{4\pi}$$
 (22)

By definition, the angular gain function, Gain (θ) , is

Gain
$$(M,\alpha,\theta) = I'(M,\alpha,\theta)/I_{i}'(M,\alpha,\theta)$$
 (23)

$$= \frac{4\pi I(M,\alpha,\theta)}{\int_{0}^{\pi} I(M,\alpha,\theta) \sin \theta \, d\theta}$$

To simplify the equations which depend upon M,α , and θ as much as possible throughout the remainder of the paper, only the parameter θ will be indicated; and the other parameters will be implied.

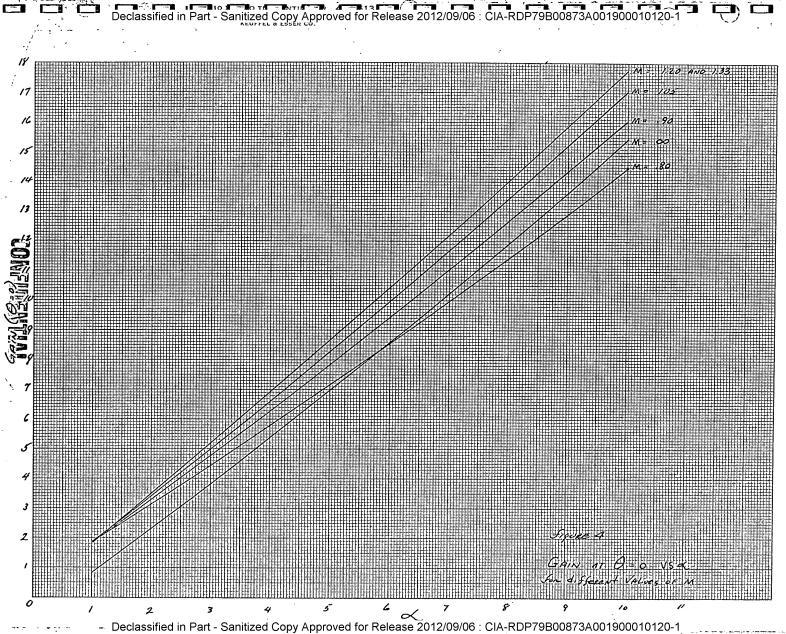
A computer program titled "Mie III" to compute $I_{II}(\theta)$, $I_{\perp}(\theta)$, $(I_{II}(\theta) + I_{\perp}(\theta))/2$, Gain (θ) , EFF (M,α) , and the per cent polarization has been written and tested. (See program Appendic C.) This program has been used to compute scattering functions for M = .8, .9, 1.05, 1.20, 1.30, and infinite for values of α from 1 to 10. Since the values of the angular gain function are the most important parameters, they have been separated from the other data by "Mie-Compressor" and have been printed separately. They appear in data Appendix A along with plots of these data.

The angular gain functions are very similar to each other differing at most by only 5 per cent at $\alpha=5$, and 15 per cent at $\alpha=10$ among the different values of M at $\theta=0$. This is not only because curves of equal α have nearly equal gains at $\theta=0$, Figure 4, but because their shapes are so similar. It must be concluded, then, that the refractive index of the scattering particles, relative to the surrounding material, is not a significant design parameter when considering only the uniformity of the scattering function. The correlation between efficiency, the particle size α , and M is given in Table I, and Figure 5. They show that little is gained in efficiency by increasing α beyond 2.

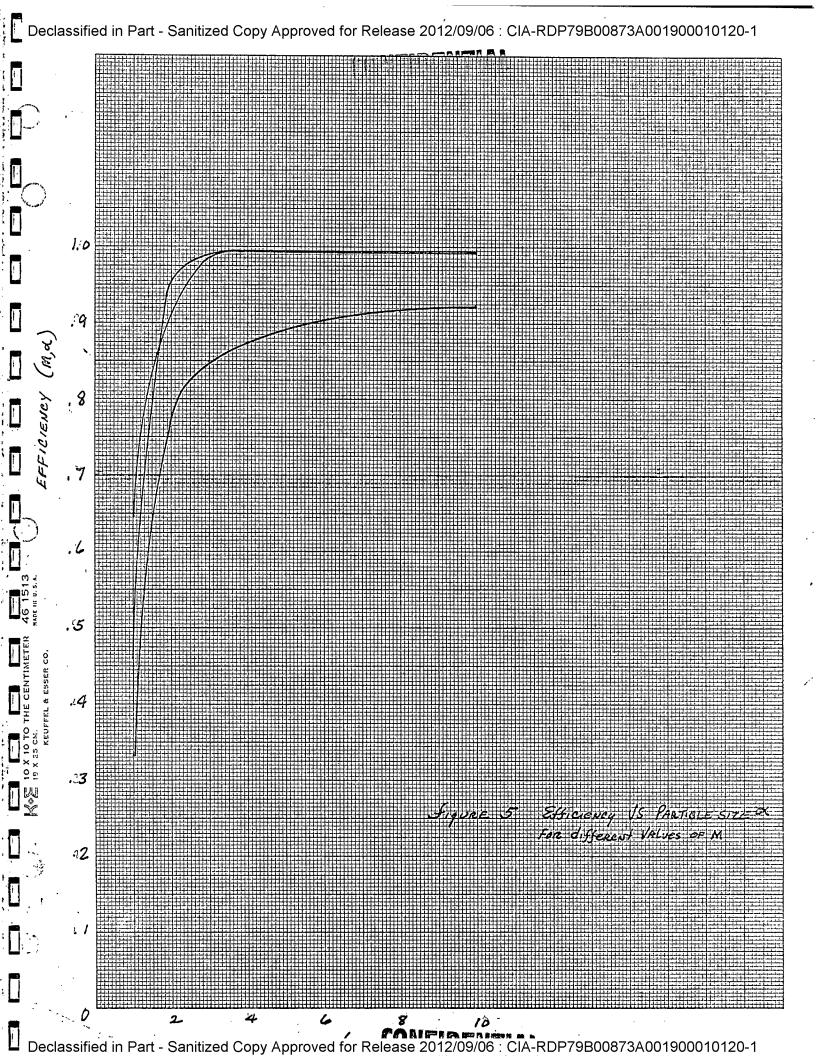
Figure 6 is a graph of efficiency versus gain at $\theta=0$ and is redundant data to Figures 4 and 5, but it is useful for visualizing the relationship between these two parameters. It can be seen that the efficiency remains constant for all values of M beyond a gain of about 3.75 which corresponds to an α of about 2.

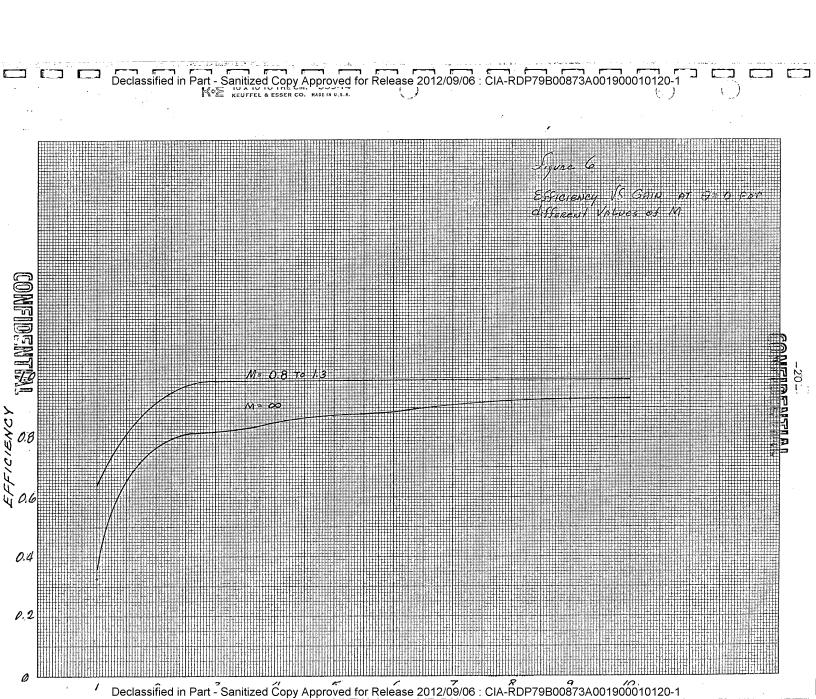
The only major difference in any of these curves is for $M = \infty$, which represents highly reflective metallic particles. Screens containing metallic particles are by far less efficient than those with finite values of refractive index. The scattering function shows many lobes, but in terms of the gain function, little detail can be seen. Because of the lower efficiencies, the gain curves are much different than those for corresponding α at finite values of M.

This analysis is only valid inside the diffusing material because, in general, there will be a medium



19.								
α/M		.8		.9	1.05	1.20	1.30	M=0.0
1	The same of the sa	.6413		.6432	.6472	.4554	.6580	.3371
2		.9186		.9351	.9596	.9766	.9784	.7621
3		.9945		.9942	.9853	.9821	.9825	.8281
4	•	.9922		.9940	.9957	.9895	.9787	.8500
5		.9975	•	.9977	.9978	.9945	.9884	.8710
6		.9972	i .	.9988	.9981	.9966	.9908	.8848
7	* .	.9988		.9987	.9994	.0000	.9 911	.9010
'. 8	•	.9982		.9995	.9993	.9973	.9903	.9109
9		.9991		.9994	.9994	.0000	.9864	.9202
10		.9988	•	.9996	.9996	.9976	.9803	.9255





of different refractive index around the screen, and light emerging from the screen will be refracted at this interface. The correspondence between θ the angle inside the medium and θ ' outside is given by Snell's law.

$$\theta' = \sin^{-1} (n \sin \theta) \quad (24)$$

where n is the relative index of refraction between the screen material and the surrounding medium, usually air.

This refractive index boundary also modifies the intensity of light passing through, depending upon its polarization. The reflection coefficients for the parallel and normal components are given by

$$R_{N}(\theta) = \left(\frac{\sin (\theta - \theta')^{2}}{\sin (\theta + \theta')}\right), \qquad (25)$$

$$R_{p}(\theta) = \left(\frac{\tan (\theta - \theta')}{\tan (\theta + \theta')}\right)^{2} \tag{26}$$

where parallel and normal refer to the angle between the electric field vector, and the plane formed by the incident beam and the reflected and refracted components, Figure 7.

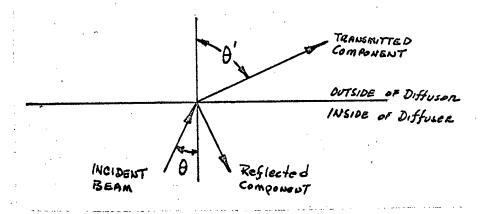


Figure 7. Refraction Geometry

If there is no absorption, then all the other light must be transmitted and the two transmission coefficients are

$$T_{N}(\theta) = 1 - R_{N}(\theta) \qquad (27)$$

and

$$T_{\mathbf{p}}(\theta) = 1 - R_{\mathbf{p}}(\theta) \qquad (28)$$

Figure 8 shows $T_N(\theta)$ and $T_p(\theta)$ as a function of the angle θ . They both must be zero beyond $\theta' = \sin^{-1} (1/n)$ as this is the critical angle θ_C inside the medium.

This refraction of the scattered light for n > 1 acts to broaden the scattering function which helps to make the screen illumination more uniform. Any pencil of light making an angle with the normal to the boundary greater than $\theta_{\rm C}$, will be totally internally reflected regardless of its polarization. For n = 1.5, $\theta_{\rm C}$ is about $42^{\rm O}$. The resulting intensity I'(θ), taking into account these losses, is

$$I'(\theta) = I_N \cdot I_N(\theta) + I_p \cdot I_p(\theta)$$
 (29)

where $I_N(\theta)$ and $I_p(\theta)$ are the two polarized components of the scattered intensity. Therefore, a new efficiency function, EFU, must now be defined as

$$EFU = \frac{2\pi}{I_0} \int_0^{\theta_C} \left[I_p(\theta) \cdot T_p(\theta) + I_N(\theta) \cdot T_N(\theta) \right] \sin\theta \, d\theta \, (30)$$

Correspondingly, the fraction backscattered EBU is

$$EBU = \frac{2\pi}{I_0} \int_{\pi-\theta}^{\pi} [I_p(\theta) \cdot T_p(\theta) + I_N(\theta) \cdot T_N(\theta)] \sin\theta d\theta (31)$$

Clearly, the light which is scattered between $\theta_{\,\rm C}$ and π - $\theta_{\,\rm C}$ is internally trapped by total internal

reflection until it is scattered at an angle less than $\theta_{\mathbf{C}}$ or greater than $\pi - \theta_{\mathbf{C}}$. The fraction of the light trapped is

$$ETU = 1 - (EFU + EBU) . \tag{32}$$

A second computer program, "MIE-S3", has been written which adjusts the angular gain functions for refraction and losses owing to reflection at the screen-air interface. The data on the corrected angular gain functions are given in both tabular and graphical form in data Appendix B. Tabular values of the functions EEF, ETU, and EBU are also given.

The data, Gain (θ) , is not strictly valid beyond $\alpha = 5$; however, for α greater than 5 the shape of the Gain (θ) curves still give some measure of the increase in the directivity with the particle size parameter α .

The most obvious differences between the data of Appendix A and B, are the broadening of the gain functions because of refraction at the air-screen interface. This can be seen by comparing the angular gain functions for different M and equal α . through the gain functions are more uniform, the gain at θ = 0 is not significantly different from the uncorrected data. This was to be expected as there is no refraction and the reflection losses amount to only about 4 per cent. There are considerable differences between the old and new efficiency functions, EFF and EFU respectively, particularly at the smaller values of Figure 9 shows the distribution of intensity between the three functions, EFU, ETU, and EBU as a function of α , for six different values of M. The backscattered fraction, EBU, is very small compared with the fraction ETU which is internally trapped and is responsible for the major portion of the losses. Backscattering is only significant for values of α less than 2, except where M is infinite.

Declassified in Part - Sanitized Copy Approved for Release 2012/09/06 : CIA-RDP79B00873A001900010120-1 . 8 TU FUNCTIONS EFU, ETU, AND EBU AS FUNCTION OF C FOR

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The fraction EFU contributes directly to the image, while the fraction ETU adds an ambient light level which degrades the image by lowering contrasts. Generally, less than half of ETU is effective in terms of directing trapped light out of the front of the screen to viewers.

To see how ETU effects the contrast of the projected image, let the contrast γ of an image be defined as

$$\gamma = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{C - 1}{C + 1}$$
 (33)

where I_{max} and I_{min} are the maximum and minimum intensities of some type of bar pattern; C is called the contrast ratio, $C = I_{max}/I_{min}$. When a screen is illuminated with a pattern of a given contrast ratio, energy from all parts of the pattern contributes to the total amount of light trapped. Of the total amount trapped, only a given fraction V will pass through to the viewers. Thus, the contrast γ_i of the final image can be shown to be

$$\gamma_{i} = \gamma_{o} \cdot \gamma_{T}$$
 (34)

where

$$\gamma_{T} = \frac{EFU}{EFU (1 - 2V) + 2V} , \qquad (35)$$

and where $\gamma_{\rm O}$ is the contrast of the pattern for ETU = 0. The contrast, $\gamma_{\rm T}$, being a function of the efficiency EFU, acts to reduce the contrast of detail on the screen.

For V = 1/2, (34) simplifies to

$$\gamma_i = \gamma_o \cdot EFU$$
 (36)

where the contrast falls linearly with the efficiency, EFU. The backscattered component only decreases the overall efficiency and has little affect on image quality.

The sum of ETU and EBU is a measure of the screen's sensitivity to front lighting. is because only the light which enters the screen from the viewing side, and is either backscattered or trapped, is of concern. The amount which passes completely through the screen has no direct effect on the quality of the projected image. all of the light from the viewing side should pass through the screen. In general, the more transmitting, i. e., the less diffusing the screen, the less sensitive it is to ambient light. This is important because in many applications the display will be viewed with a certain amount of room light present. The greater the difference between the ambient intensity and the screen brightness, the better will be the conditions for obtaining good quality on the projection screen.

An unsatisfactory solution to this problem often used is to put a light absorbing material into the screen. The absorption tends to reduce the sensitivity to ambient light by absorbing a large fraction of it. However, it also reduces the overall efficiency of the projection system by the same amount, and in many applications where total power is of utmost importance such losses cannot be tolerated. The light which passes through the screen should not illuminate any highly reflecting objects behind it, as rear projection screens are very sensitive to stray back illumination.

Along with parameters such as particle size and relative refractive index, a given material can be characterized by the particle number density and its associated thickness. Thus far we have considered scattering only by a single particle, whereas practically, we are concerned with the combined scattering of billions of particles. One of the most important parameters is the scattering cross section $\sigma_{\rm S}$, of the scattering particles. This has units of area and represents the <u>effective</u> cross-sectional area of the particle which produces scattering.

Another parameter closely related to the scattering cross section is the efficiency factor K, which is defined as the ratio of the scattering cross section to the geometrical cross section σ_{σ} , also called the scattering coefficient.

$$K = \sigma_{S}/\sigma_{G} \qquad (37)$$

For a sphere $\sigma_g = \pi a^2$. Therefore, K is a measure of how efficiently the area σ_g produces scattering. The total scattered intensity I_s' , per geometrical cross section is

$$I_{s}' = I_{o} \cdot K . \tag{38}$$

Using (37) in (38) we get

$$\frac{\mathbf{I_s'}}{\mathbf{I_o}} = \frac{\sigma_{\mathbf{S}}}{\sigma_{\mathbf{q}}} . \tag{39}$$

This takes into account only the light which falls on a geometrical cross section rather than on a unit of the material containing scatterers. The

fraction F of the incident light being scattered in terms of the number of particles N, the area A of the material being illuminated, and the scattering cross section are

$$F = \frac{I_S}{I_O} = \frac{N_{O_S}}{A} \quad . \tag{40}$$

The ratio N/A in (40) can be written in terms of the particle number density ρ , and the thickness T of the material as

$$\frac{N}{A} = \rho T . \tag{41}$$

Thus, (40) becomes

$$\mathbf{F} = \frac{\mathbf{I_S}}{\mathbf{I_O}} = \rho \mathbf{T} \sigma_{\mathbf{S}} . \tag{42}$$

This assumes that each particle is completely illuminated, which actually never occurs as the particles nearer the front side of the material shadow other particles which lie further into it. From theoretical considerations, it can be shown that

$$I_s = I_o(1 - e^{-K_{\Pi}a^2\rho^T})$$
 (43)

Thus, for F = 1, the per cent of the incident light scattered is $I_s/I_0 = 63$ per cent; for F = 2, $I_s/I_0 = 86.4$ per cent; and for F = 3, $I_s/I_0 = 95$ per cent. Following this, the material must be infinitely thick for all of the light to be scattered. The question is: for what value of F is enough of the light scattered so the specular component is unnoticeable? There can be no definite theoretical answer to this; however, this limiting value will be determined experimentally.

This can be done simply by measuring the intensity of the specular component for several different thicknesses and evaluating the exponent of (43) for the thickness which has the optimum amount of scattering.

To ensure color fidelity of the projected image, the scattering coefficient should not change rapidly with α . For example, if a particle is illuminated by two different wavelengths, λ_1 = .45 micron and λ_2 = .65 micron, the ratio of the two α 's is

$$\frac{\alpha_1}{\alpha_2} = \frac{\lambda_2}{\lambda_1} \qquad (44)$$

The scattering function for λ_1 and λ_2 is determined by the scattering functions evaluated at α_1 and α_2 respectively. Therefore, if the angular scattering functions are significantly different, as in Figure 10, and the power spectral density is uniform, the center of the screen would have an excess of blue while the edges would have an excess of red. A good color balance would only occur around

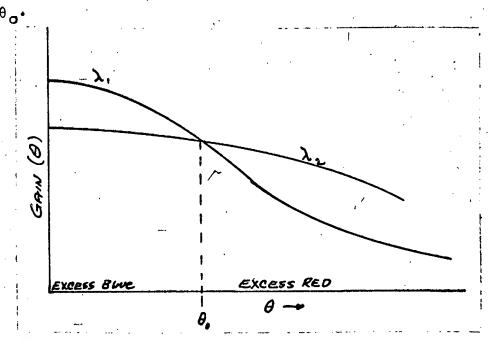


Figure 10. Poor Color Balance Resulting from
Differences in the Shapes of the Angular
Gain Functions at Two Wavelengths.

The scattering coefficients are plotted as a function of α for different values of M, Figure 11. The important parameter is $K_{r'}$, the ratio of the scattering coefficients at the two values of α .

$$K_{r}(M,\alpha_{1}) = \frac{K(M,\alpha_{1})}{K(M,\alpha_{2})} \qquad (45)$$

This ratio is plotted as a function of α_1 in Figure 12. The limit of $K_r(M,\alpha_1)$, for small alpha, is $(1.445)^4 = 4.36$, which is the limiting case of Rayleigh scattering. $K_r(M,\alpha_1) = 1$ implies the scattering cross section at α_1 and α_2 are equal, and the intensities of the scattered light are the same. When $K_r(M,\alpha_1) = 2$ the scattering cross section at α_1 is twice that at α_2 .

Using Equation (43) and denoting the scattering coefficient for α_1 by K_1 and for α_2 by $K_{2'}$ we have

$$\frac{I_{s1}}{I_{o}} = 1 - e^{-K_{1} \pi a^{2} \rho T}$$
 (46)

and

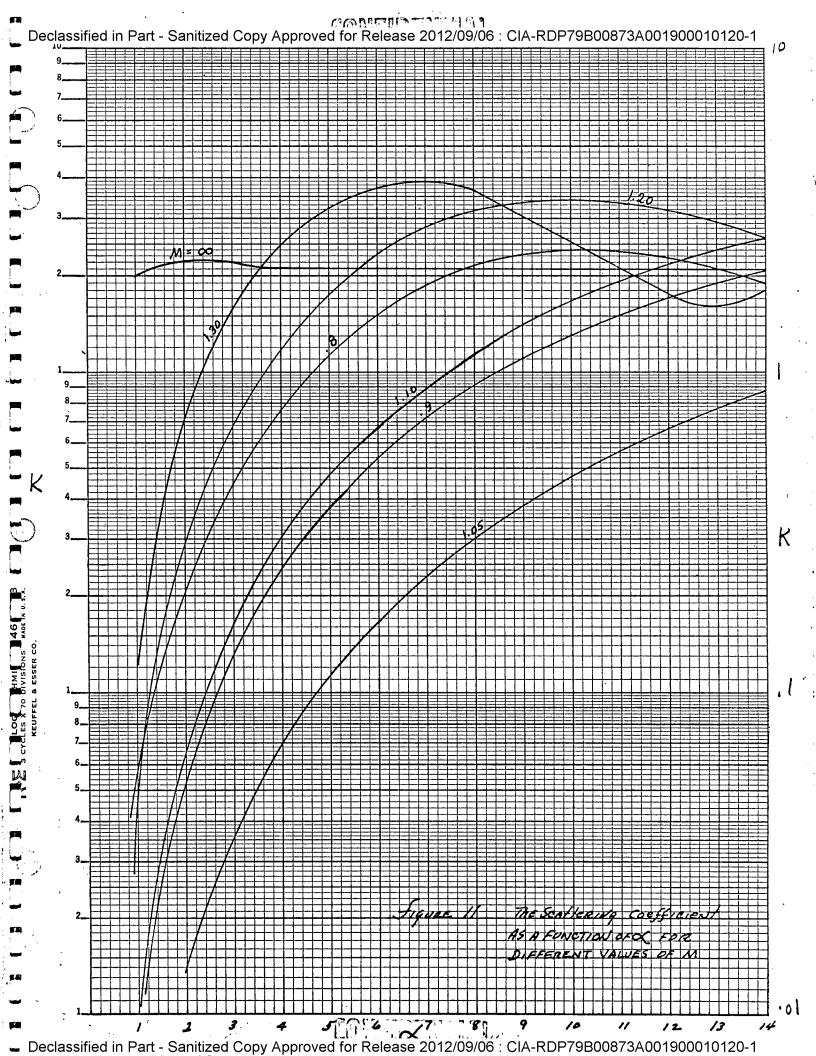
$$\frac{I_{s2}}{I_{o}} = 1 - e^{-K_2 \pi a^2 \rho T} \qquad (47)$$

The ratio R of the scattered intensities is

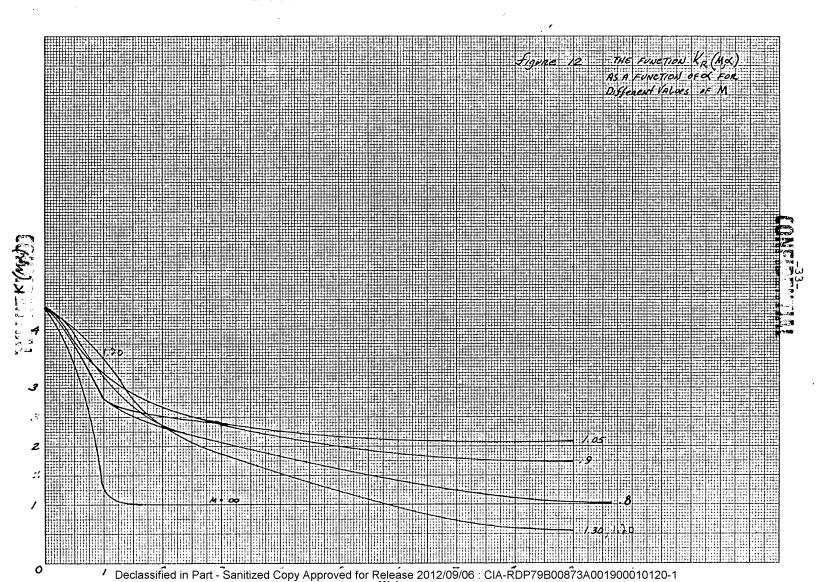
$$\frac{I_{s1}}{I_{s2}} = R = \frac{1 - e^{-K_1 \pi a^2 \rho T}}{1 - e^{-K_2 \pi a^2 \rho T}}$$
 (48)

Now let

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$$K_1 \pi a^2 \rho T = U$$

or

$$\pi a^2 \rho T = \frac{U}{K_1} \quad ; \tag{49}$$

U is referred to as the "optical density" of the scattering material. For an optical density of unity, U=1, the intensity of the unscattered beam has fallen to $\frac{1}{e}$ its initial value after passing through a thickness T.

Using (49) in (48), we have

$$R = \frac{1 - e^{-U}}{1 - e^{-UK_2/K_1}} {.} {(50)}$$

Solving for the ratio of scattering doefficients at the two different wavelengths, we have

$$\frac{\kappa_{\underline{1}}}{\kappa_{\underline{2}}} = \frac{\underline{U}}{\log_{\underline{e}}\left[\frac{R}{R-1+\underline{e}^{-\underline{U}'}\right]}} . \tag{51}$$

The ratio K_1/K_2 is plotted for U=1 as a function of R, Figure 13. Thus, by specifying the maximum tolerable ratio of the scattered light at two different wavelengths and the "optical density" of the material, we have defined the maximum permissable ratio of the scattering coefficients. As an example for U=1 and $I_1/I_2=1.5$, we see that K_1/K_2 must not be more than 1.85.

Clearly, values of R and ${\rm K_1/K_2}$ near unity are the most desirable, because the degree of scattering is then independent of wavelength and only differences between the two gain functions for α_1 and α_2 are responsible for any residual color. When

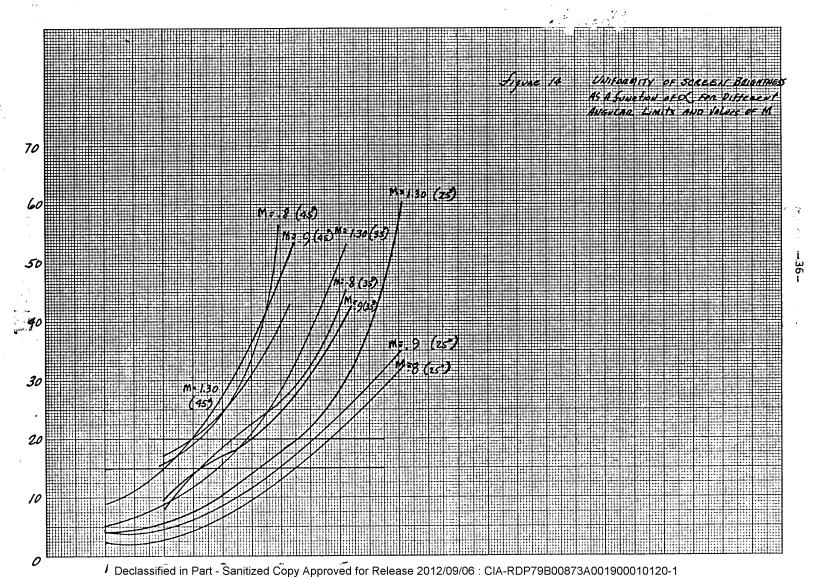
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 $K_r(M,\alpha_1) > 1$, a greater fraction of blue light is scattered, making the color characteristics of the material more undesirable.

The refractive index is therefore a significant design parameter, but in an unexpected way it can be seen from Figures 12 and 13, that the most promising materials have refractive indices as far from unity as possible but not infinite, i. e., the best values of M are .8, .9, and particularly 1.30.

Requirements in the contract specify the angular gain function should not change by more than ±15 per cent over a viewing angle of ±45°. This requirement, in terms of the gain function already computed, is shown in Figure 14. ordinate is the variation in intensity from 0° to $\pm 45^{\circ}$, 0° to $\pm 35^{\circ}$, and 0° to $\pm 25^{\circ}$ plotted against particle size α for different values of M. desirable to use the largest particle size practical because of the higher efficiencies and less degradation of the projected image by light which is trapped. Clearly, the major factor limiting the use of large particles is the resulting nonuniformity of the screen. As can be seen from Figure 14, the uniformity is a very critical function of the angular limits and α .

To strictly meet the requirements set forth, the particles must be no larger than $\alpha=2$, which means the gain at $\theta=0$ will not exceed 3.5; the overall efficiency will be somewhere near 65 per cent with the remaining 35 per cent of the light being trapped. This trapped light will reduce the contrast of the image by almost one-third.



If, on the other hand, the limits of uniformity are chosen to be ±15 per cent over ±350, we see the particle size now moves up to $\alpha = 2.75$; the gain at $\theta = 0$ moves up to a value of 4.75; the efficiency significantly improves to a value of near 80 per cent. The contrast is lowered by only 20 per cent rather than 33 per cent, and the color fidelity is better. The second screen would be 34 per cent brighter than the first in the center and 11.5 per cent brighter at the edge. second criterion is only used as an example to show the improvements in efficiency and contrast by using slightly larger particles which give a higher gain, higher brightness screen. This type of analysis can be easily carried out rapidly for any given set of criteria using only the graphical data.

The particle densities required are governed primarily by the thickness of the samples. The thinner the sample, the higher the density of scatterers required to maintain the same amount of scattering.

Thickness and shape of the gain function are the main parameters limiting resolution. We are working toward an initial resolution of 10 lines/mm, and the desired goal is 20 lines/mm with the MTF down only 10 per cent to .9. This will require a very thin scattering layer which may possibly have to be bonded to a thicker transparent sheet for structural support. Initially in our materials program, relatively thick samples will be requested to facilitate handling and slabbing into thinner sections.

3. Specific Materials Requirements Based on our Theoretical Studies

Specifically, we have already requested samples of glass-ceramic materials, $Fotoform^R$, and sintered glasses which have the properties listed in Table II. The numbers on the left side of the

Table II. Materials Requirements

	α = 2	, α = 3	a = 4
M/D	.2 8 μ	.42 µ	.55 μ
.8 .9 1.3	8.9×10^{10} 3.3×10^{11} 2.9×10^{10}	1.6 x 10^{10} 5.8 x 10^{10} 5.1 x 10^9	5.2×10^9 1.7×10^{10} 1.7×10^9

table are relative refractive indices between the particle and the surrounding medium, those across the top are the required diameters of the particles, corresponding to values of α of 2, 3, and 4 respectively, for λ = .65 microns. In the body of the table are the required number density of particles in number/cm³. The diameter and the number density are to be held to within ± 10 per cent of the values specified.

It is essential to know exactly the physical properties of the samples of materials if these data are to be correlated with the theoretical work already completed. To aid in this, electron photomicrographs will be made of each sample for determining particle size, size distribution, and the particle density.

It is hoped there will be enough glass from each small melt to yield, after cutting, at least eight pieces measuring 40 mm x 18 mm and 5 to 7 mm thick.

Any two pieces cut from the same melt will be expected to have identical properties. To ensure the shortest turn around time from one set of melts to another, at least one-half of every melt will be directly forwarded to us for preliminary optical evaluation. Detailed evaluation will begin later, after electron microscope data have been obtained and the physical properties of the melt determined. Thus, we have started the third phase of this program, which is the evaluation of Corning Glass Works' materials for applications in rear projection screens.

B. Rayleigh Scattering

The mathematical formulations of Mie scattering theory, although elegant, are correspondingly involved and time consuming to carry out. Further, it is difficult, if not impossible, to examine separate terms relating to different parameters. However, when the size of the particles are small compared to the wavelength of illumination, their scattering properties can be described by a much simpler theory first proposed by Lord Rayleigh²⁰.

1. Theory

Consider an incident electromagnetic wave perfectly monochromatic and linearly polarized, with the electric vector along the x axis, and moving in the +z direction and is incident on a particle at the origin, Figure 15. Let the amplitude be unity and the phase angle be such that in complex representation the field at the origin is

$$\mathbf{E}_{\mathbf{x}} = \mathbf{e}^{-\mathbf{i}\mathbf{w}t} \qquad \qquad \mathbf{E}_{\mathbf{y}} = \mathbf{E}_{\mathbf{z}} = \mathbf{0}$$

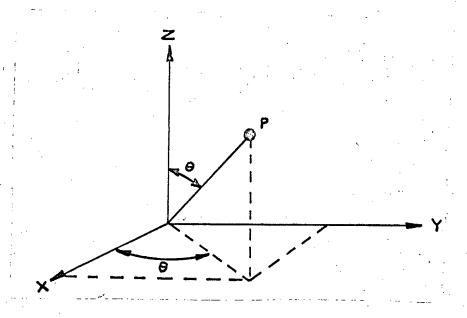


Figure 15. Coordinate System to Which the Scattering Geometry is Referred

The result of the particles being subjected to this field is that each of its elastically bound electrons is set into sinusoidal oscillation with frequency ω , and with the same phase Since the particle is small compared with the wavelength, the net scattered wave is just that which would be radiated by a single dipole oscillator with some dipole moment P. It is this property of the scattered wave, guaranteed by the smallness of the particle compared with the wavelength, that characterizes Rayleigh scattering. Throughout this discussion, it will be assumed that only scattering is responsible for removal of light from the incident, collimated, unpolarized beam, i. e., no absorption nor reflection will be considered.

The scattering cross section for these particles is given as

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$$\sigma_{s} = \frac{8}{3} \pi \left(\frac{2\pi}{\lambda}\right)^{4} |\beta|^{2}$$
 (52)

where β is the polarizability of the scattering material. In general, β is a complex vector because of absorption and anisotropy of the particles. This can be written

$$|\beta|^2 = i^2 |\beta_x|^2 + j^2 |\beta_y|^2 + k^2 |\beta_z|^2$$

where i, j, and k are the direction cosines of the incident electric field with respect to the three main axes of the polarizability tensor.

Assuming independent spherical particles, $\mid\beta\mid^{2}$ has been found to be 21

$$|\beta|^2 = a^6 |\frac{M^2 - 1}{M^2 + 2}|^2$$
 (53)

where a is the radius of the particle and M is the index of refraction of the particles relative to the surrounding supporting medium. M is real only when there is no absorption. The scattering cross section for small spherical particles using (52) and (53) is

$$\sigma_{s} = \frac{128}{3} \frac{\pi^{5} a^{6}}{\lambda^{4}} \left| \frac{M^{2} - 1}{M^{2} + 2} \right|^{2} . \tag{54}$$

The angular intensity distribution of scattered light is

$$I(\theta) = \frac{(1 + \cos^2 \theta)}{r^2} \cdot \frac{8\pi^4}{\lambda^4} \cdot a^6 \cdot \left| \frac{M^2 - 1}{M^2 + 2} \right|^2 \cdot I_0 \quad (55)$$

where r is the distance from the scattering center. The gain function is, therefore,

Gain
$$(\theta) = \frac{3}{4} (1 + \cos^2 \theta)$$
 (56)

2. Feasibility of Using Rayleigh Scattering Materials as Rear Projection Screens

We now wish to determine the feasibility of these materials as rear projection screens using the equations given in the preceeding section. The various terms will be studied to better understand how each contributes to the overall properties of Rayleigh scattering.

a. Dependence on the Relative Refractive Index M

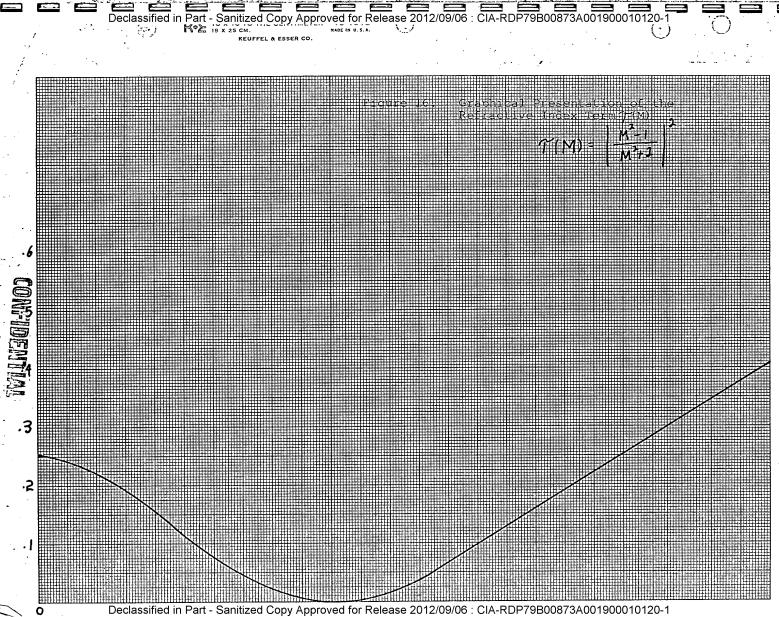
Consider first the dependence of the scattering function and scattering cross section on the refractive index M

$$M = \frac{n_p}{n'} , \qquad (57)$$

where n_p and n' are the refractive indices of the particles and medium respectively and are assumed to be real. The function $_{\text{T}}(M)$, which expresses this dependence, is

$$\tau(M) = \left| \frac{M^2 - 1}{M^2 + 1} \right|^2 . \tag{58}$$

The behavior of $_{T}$ (M), as a function of M, can be seen from Figure 16. As M approaches infinity, i. e., reflecting metallic spheres, $_{T}$ (M) approaches unity. For practical purposes .6 \leq M \leq 1.7. It seems pointless to consider values of M less than .6 as this requires a very high refractive index for the matrix material, and a metallic matrix is implied for M = 0. Therefore, to have as large a scattering cross section as possible, M should be as far from unity as possible. Clearly for M = 0 the glass is "homogeneous" and transparent.



b. Wavelength Dependence

Consider next the influence of wavelength on the relative size of the scattering cross sections at two different wavelengths, and the associated scattering function. Choosing λ_1 = .45 microns, and λ_2 = .65 microns, we have as the ratio of scattering cross sections and intensities of scattered light

$$\frac{I(\lambda_1, \theta)}{I(\lambda_2, \theta)} = \frac{\sigma_{s1}}{\sigma_{s2}} = \left(\frac{\lambda_2}{\lambda_1}\right)^4 = 4.3 \quad . \tag{59}$$

This means if we illuminate a screen composed of Rayleigh scatterers with light from .45 to .65 microns, there will be 4.3 times as much light scattered at .45 microns as at .65 microns, assuming only single scattering at .45 microns. Thus, the scattered light will have an excess of blue light, while the specular component will have an excess of red. On the other hand, if we require all of the incident light at .65 microns to be singly scattered we must accept mixed higher order scattering over the whole spectral region. Much of the light at shorter wavelengths has been scattered so much that, at best, 50 per cent of it has been scattered in . the forward direction, and only a fraction of this will come through the screen to the viewers because of total internal reflection.

It is instructive to compute the scattering coefficient K_1 and K_2 for the two extreme wavelengths, λ_1 and λ_2 , which after the evaluation of the constants in (54) simplifies to,

$$K_{i} = 415 \cdot (\frac{a}{\lambda_{i}})^{4} .$$
 (60)

The value of the refractive index term $_{\text{T}}$ (M), was chosen as .1 from Figure 16, which corresponds to M = 1.55. Thus, using a particle radius of a = .02 microns, which is near the upper limit of particle size for Rayleigh scattering at visual wavelengths, gives

$$K_1 = 1.62 \times 10^{-3}$$
 (61)

and

$$K_2 = 3.74 \times 10^{-4}$$

This is to say the effective cross sections which produce scattering are about 1000 times smaller than the geometrical cross section. Therefore, large particle concentrations (number/cm³) are required to sufficiently diffuse the incident light.

One of the major disadvantages of Rayleigh scattering is the strong wavelength dependence of the scattering function. The blue excess in the scattered light can be corrected by using a filter with a spectral transmittance $T(\lambda)$, of

$$T(\lambda) = K\lambda^{4} \qquad . \tag{62}$$

If such a filter can be used, the screen will have a maximum efficiency of 23 per cent, assuming all the light passes through to the viewers. This approach will serve to improve the balance color, but efficiency will be severely reduced.

Consider the projection screen consisting of Rayleigh scatterers, Figure 17. reaching an observer, 0', outside the solid angle, will consist only of scattered light and no specular component. This light will contain an excess of blue which could be balanced by using the spectral filter previously described. Inside, most of the screen will be seen by scattered light. Unfortunately, for single scattering at .45 microns, an observer, 0, will be able to see through the screen at wavelengths less than this and see the source by the specular component which will have an Thus, it seems impossible excess of red light. to compensate simultaneously for the excess of blue in the scattered component and the excess of red in the specular component. undesirable to have any specular transmission, from efficiency and viewing considerations, one might suggest increasing the scattering in the screen until all of the light is at least singly. scattered. This approach is impractical because of the low efficiencies.

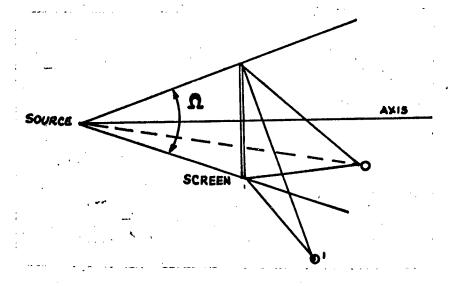


Figure 17. Two Viewing Geometries, with and without a Specular Component

c. Angular Dependence

The angular dependence of the scattering function given by (55) is valid only for single scattering of unpolarized light. Therefore, when a range of wavelengths is used and mixed scattering occurs, one can expect the shape of the scattering function to be significantly different at different wave-From the symmetry of the scattering function, Figure 18, it is clear that only half of the incident light is scattered through the material and the other half is backscattered toward the projector. Thus, under the best possible conditions, i. e., monochromatic illumination and complete single scattering, the efficiency of the material cannot exceed .5. It is important to remember that since the efficiency is based on scattered light only, any specular transmission results in a decrease in the efficiency.

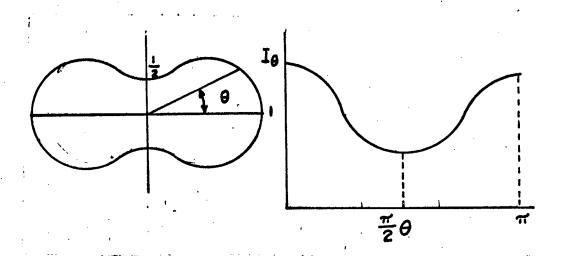


Figure 18. The Normalized Polar and Rectangular Forms of the Scattering Diagram for Rayleigh Scattering from a Monochromatic Unpolarized Beam

After considering only total internal reflection, less than 19 per cent of the light scattered comes through the screen to form an image, and an equal amount is backscattered. The fraction of this trapped exceeds 61 per cent which degrades the contrast of the image by a factor of 1.7.

d. Polarization Considerations

Another effect of the angular scattering is that the scattered light is polarized to a degree depending on the angle θ . The fractional polarization $P(\theta)$ is given as

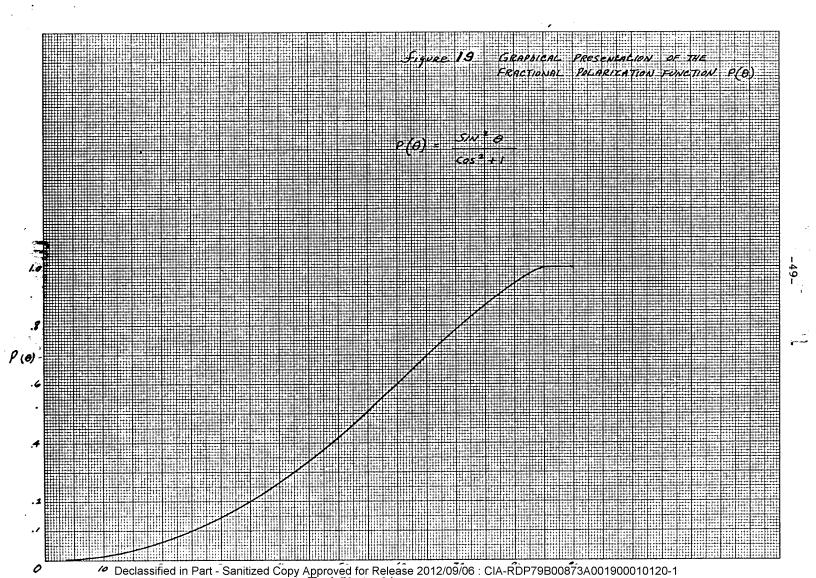
$$P(\theta) = \frac{\sin^2 \theta}{1 + \cos^2 \theta} , \qquad (63)$$

and its behavior is shown in Figure 19. The \cos^2 term, in the parentheses of Equation (55), gives the relative intensity of the scattered component whose electric vector lies in the plane defined by the incident beam and the observed scattered beam. The term corresponding to the factor unity in the parentheses refers to the scattered component whose electric vector is perpendicular to the plane of observation. When $\theta = 90^{\circ}$, it is seen that the scattered light is plane polarized with its electric vector perpendicular to the incident beam, a well-known result.

e. Conclusion

Rayleigh scattering theory has been considered and the general scattering function investigated. Separate terms in the scattering function were considered individually and numerically evaluated to better understand how they contribute to the

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scattering function. We have been able to show theoretically that rear projection screens made from Rayleigh scattering materials are unsatisfactory for a number of reasons. They are inefficient although the scattering function is very broad and uniform. Correspondingly, the resolution of such screens is very low. The strong wavelength dependence of the scattering function and scattering cross section impose nearly impossible constraints which, when not met, result in screens which have very poor color characteristics. Applications for these materials probably lie only in low gain, low resolution, monochromatic screens.

V. Corning Glass Works' Materials

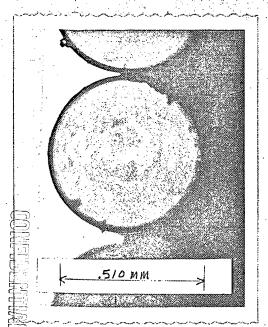
Some effort has been directed toward other types of rear projection screen materials which do not depend upon volume scattering. It is expected that these alternate approaches will depend as strongly upon available Corning Glass Works' technologies as upon specific materials. Only those approaches which have been considered in some detail are reported.

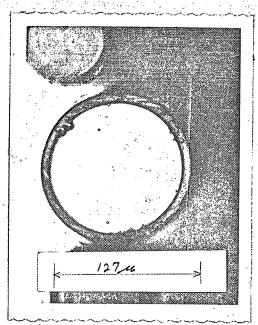
A. Hollow Fibers

We have been investigating the feasibility of using hollow optical fibers with highly reflective coatings as a rear vew projection screen material. Conventional optical fibers consist of an inner glass core and a surrounding outer cladding of a lower refractive index material. The attenuation of light in a fiber is a complex phenomena, but for practical purposes the internal losses are due to inherent properties of the dielectric core and not to imperfect total internal reflection.

A modified concept is proposed here. This proposes the use of hollow tubes with highly reflective inside walls where losses are now governed only by the reflective properties of the coating and not by the loss tangent of the core. These can be manufactured more easily than the cladded solid core fibers, thereby making them This type of optical fiber is fabricless expensive. ated by Corning (without reflective coatings) and is illustrated in Figure 20. Such hollow tubes have been fabricated down to 10 microns in inside diameter with good control of open area to wall area. In the 10-20 micron diameter region this ratio can be as much as 70/30. At smaller diameters, wall thickness remains constant, but the hole gets smaller and smaller until it becomes a solid fiber. The two major problems associated with







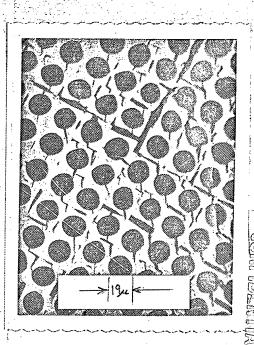


Figure 20. Photomicrographs of two samples of hollow fibers and one fiber array to be used in preliminary plating studies.

producing acceptable fibers are: (1) difficulties in putting the highly reflective coating on the inside, and (2) the reflectivity of the coating.

One of the assumed advantages of using hollow fibers as a rear projection screen material is their ability to accept a large angular bundle of light. Unfortunately, a large acceptance angle does not guarantee a large usable exit angle.

The number of reflections K, is related to the length-to-width ratio r, of the fibers and the angle of incidence θ , measured from the axis of the fiber, Figure 21, by

$$K = r \tan \theta \qquad (64)$$

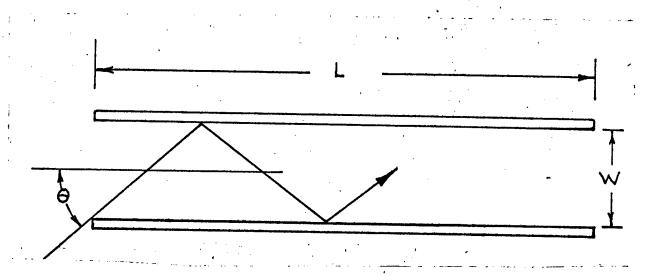


Figure 21. The Propagation of Light Through a Hollow Tube

The fraction of light transmitted I/I_0 , is determined by K and the reflectivity R,

$$I/I_{O} = R^{K} \qquad \bullet \tag{65}$$

A typical value of r might be 300, which corresponds to an inside diameter of 15 microns and a length of 5 mm. Clearly, K grows very fast because of the large value of r. Therefore, R must be very near unity. Unfortunately, metals do not have such reflectivities. Table III gives some typical values of the reflectivity for a few common materials 22.

Assume a value for the reflectivity R, of .93 (silver). Two curves, one for r = 60 and another for r = 300 are plotted, Figure 22. This clearly shows the consequences of R not being near unity, i. e., an extremely small "effective" acceptance angle results.

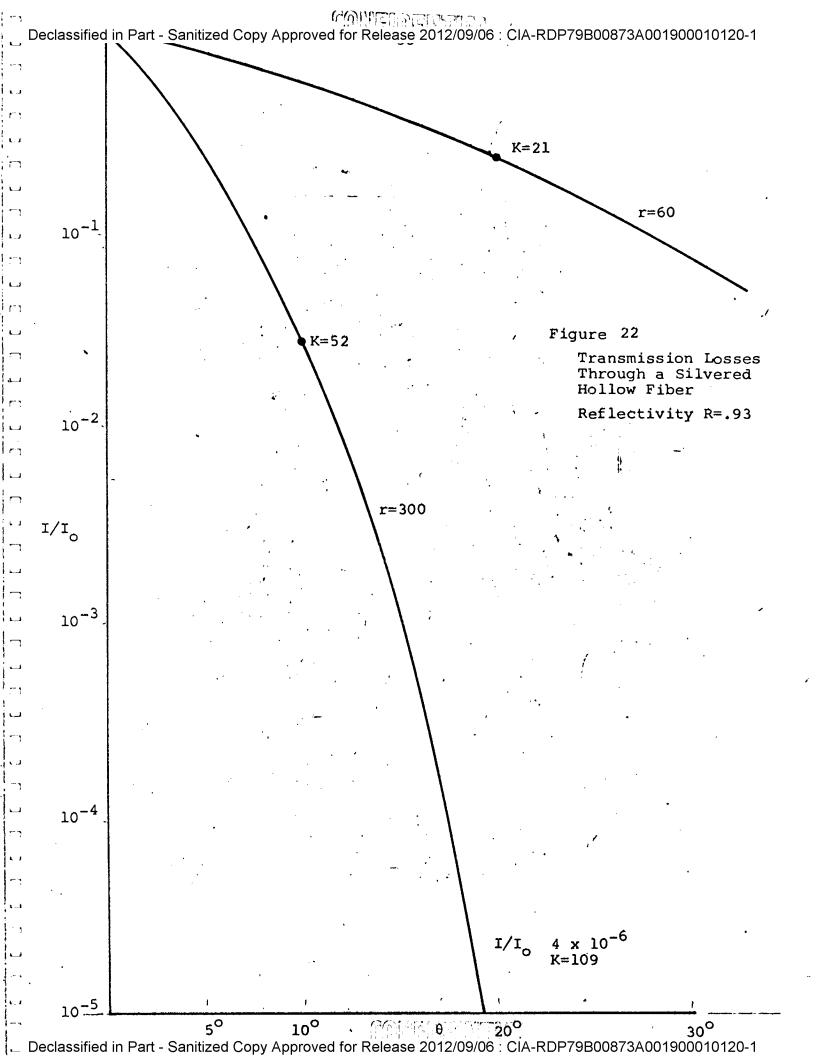
The exact value of the effective acceptance angle depends upon the transmission limit one chooses. For example, at r = 300, if one chooses the limit of $I/I_0 = .5$, the acceptance angle is less than 2.5° . On the other hand, if we choose the limit by the criterion $I/I_0 = .1$, the acceptance angle extends to 7° , an increase of almost 3. In either case the acceptance angle is far too small.

An experiment was conducted to verify this theoretical work using two, silvered, flat, parallel mirrors, one above the other. Light was incident at different angles and the resulting transmission measured. The results are shown graphically in Figure 23. These data, for r = 10, indicate a constant reflectivity of .96, which is realistic considering the surface was a newly deposited silver film. The problem is made more complicated by differences in the reflectance at two

Table III. Reflection Coefficients of Surfaces for "Incandescent" Light

	·	· ·	•
Material	Nature of Surface	Coefficient	Authority
Aluminum, "Alzak"	Diffusing	0.77-0.81	3
"Alzak"	Specular	0.79-0.83	3
on Glass	First Surface	0.82-0.86	4
Polished	Specular	0.69	3
Black Paper	Diffusing	0.05-0.06	4
Chromium	Specular	0.62	4
Copper	Specular	0.63	4
Gold	Specular	0.75	1
Magnesium Oxide	Diffusing	0.98	5
Nickel	Specular	0.62-0.64	1.3
Platinum	Specular	0.62	1 -
Porcelain Enamel	Glossy	0.76-0.79	3
Porcelain Enamel	Ground	0.81	3
Porcelain Enamel	Matt.	0.72-0.76	3
Silver	Polished	0.93	1
Silvered Glass	Second Surface	0.88-0.93	3
Snow	Diffusing	0.93	2
Steel	Specular	0.55	1
Stellite	Specular	0.58-0.65	· 4

25X1



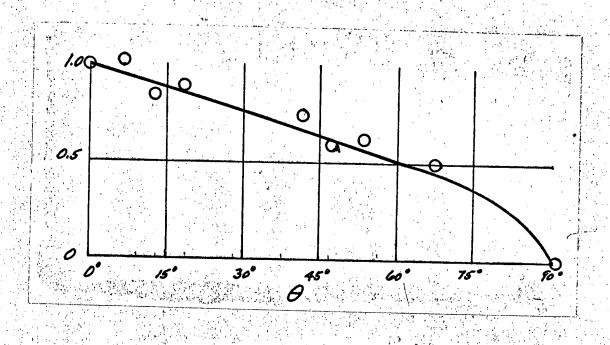


Figure 23. Measured Transmission of Two Silvered Plates

different wavelengths $^{23-25}$. This means that as more and more reflections occur, the light becomes weighted either to the blue or to the red depending on which wavelength the reflectance is higher. The intensity ratio of the red to blue is given in Table IV, note the strong color shifts for K = 100.

It is obvious from the above discussion, that the limitations imposed by the metallic coatings are by far too severe to consider the application of metallized hollow tubes for application in rear projection screens.

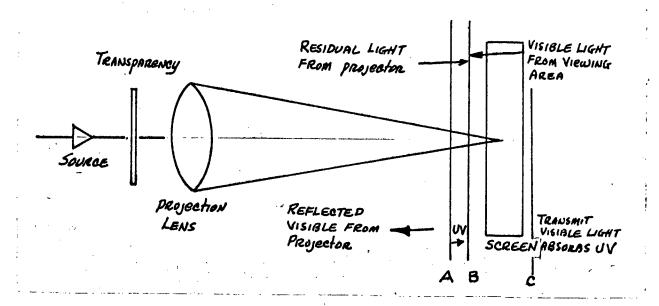


Figure 24. Construction of an Ultraviolet Sensitive Screen

2. A Louvered Screen

A louvered screen, discussed in previous technical reports and patented by A. H. J. De Lassus St. Genies ²⁶⁻²⁸, has been constructed, Figure 25. The screen was made by placing 13 - ½" plates of plastic measuring 1" x 4" together as shown in Figure 26. A hole was drilled down each side and bolts were inserted and tightened holding the blocks firmly together. The top and bottom of the stack was then machined flat to a .35" overall thickness, and the two faces were sanded and polished. Each block was numbered and the stack disassembled. One inside face of each block was sanded so that when aluminized it would be diffusely reflecting. Both faces were aluminized and the stack

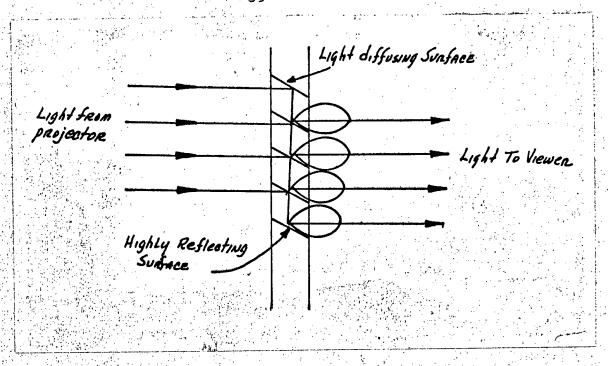


Figure 25. Optics of the Louvered Screen

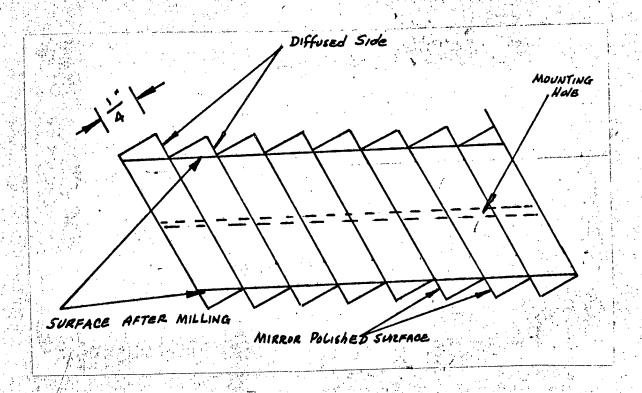


Figure 26. Construction of the Louvered Screen

reassembled. The resulting screen has a usable area measuring 3 - 3/4" x 3 - 3/8", Figure 27.

An analysis of this model is being made to determine what major optical problems exist when viewing this type of screen, and also, some of the technologies which may be of value in building practical samples.

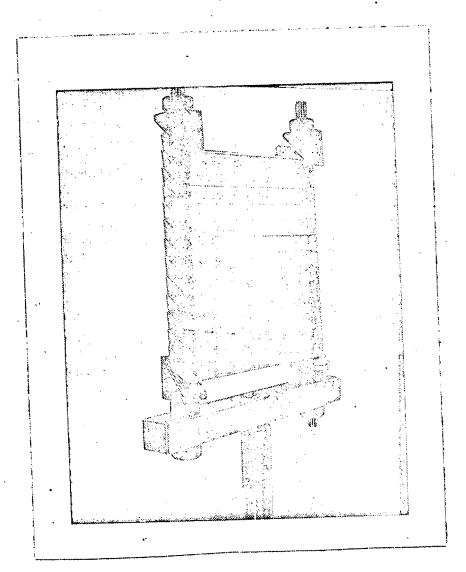
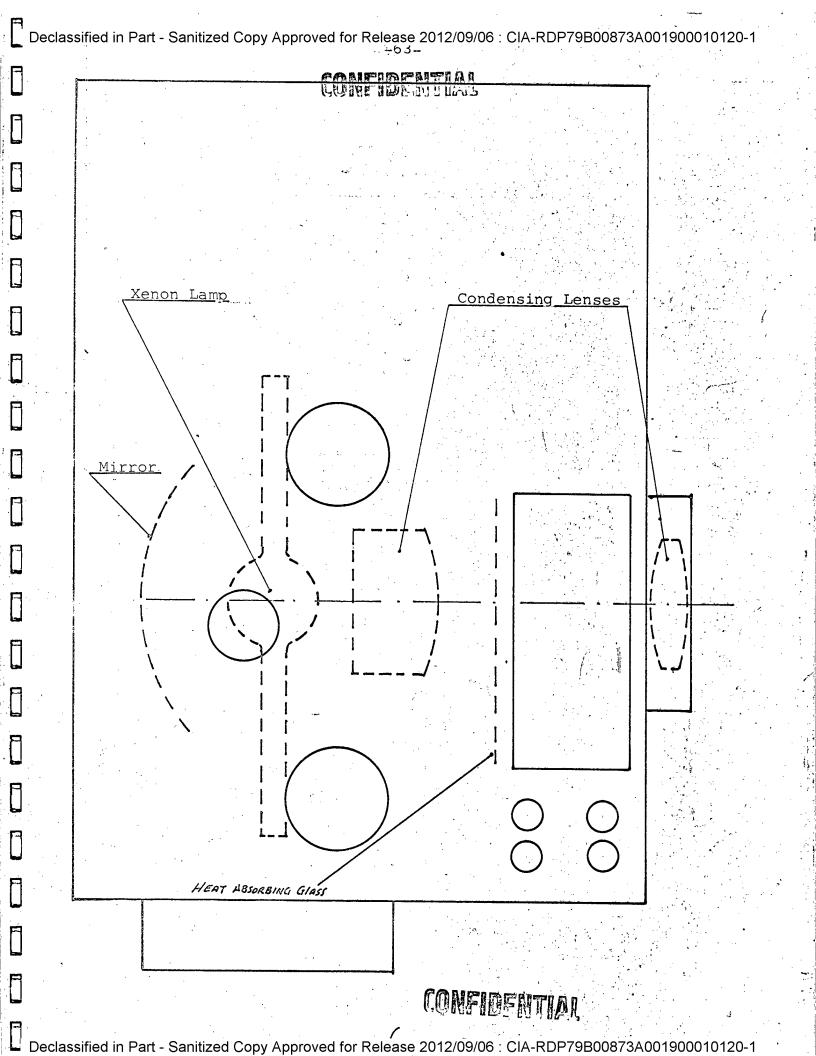


Figure 27. A Preliminary Louvered Rear Projection Screen Model

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DETAILS SOURCE CONTINUES CONTINUES OF SHAPE HOUSE O

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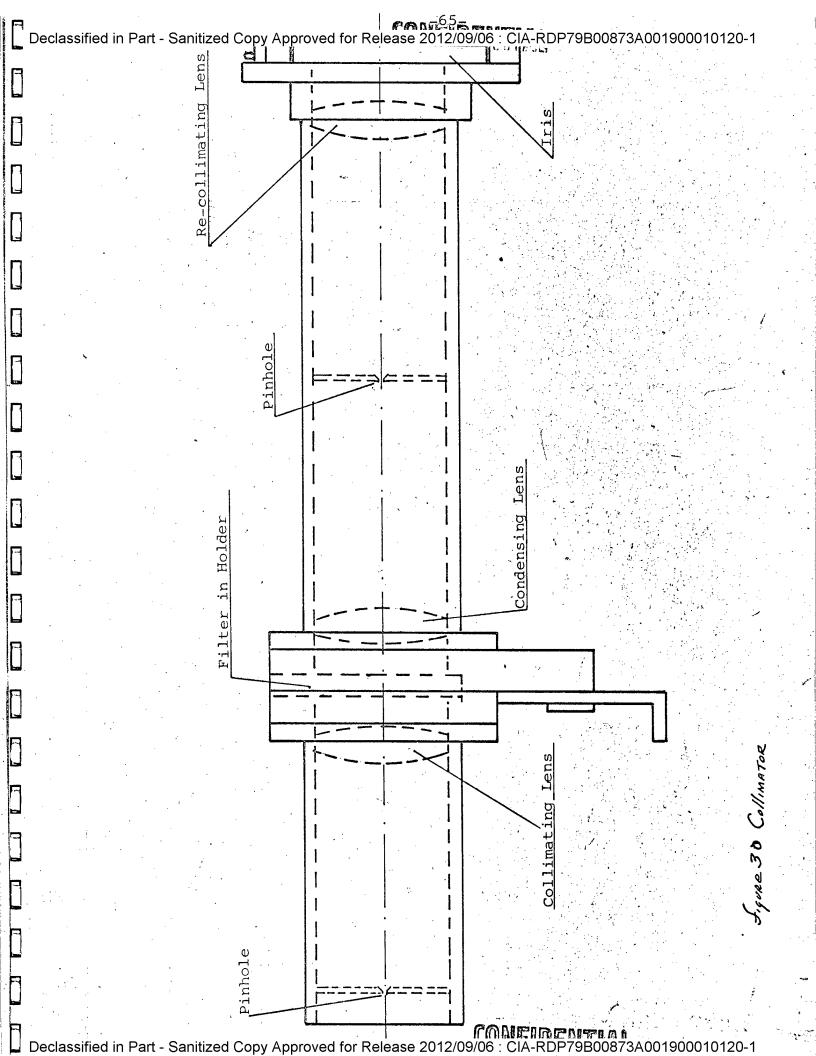


A heat absorbing filter, which cuts out the major portion of infrared radiation, mounts between the two condensing elements. The second element focuses the collimated beam from the first onto a pinhole aperture at the front end of the collimator.

Collimator

Immediately behind the lamp housing, but apart from it, is the collimating unit which consists of a collimator, a filter holder and a recollimating unit, Figure 30. Light incident on the first pinhole is collimated by the first lens, then passes through the filter holder. The holder accepts any 2 x 2 inch filter which may either be a narrow band interference filter, a broadband spectral filter, or a polarizing filter. the beam is spread over a larger area of the filter, there is little chance it will be damaged by excessive power as it might be if it were nearer the source in a more concentrated beam. interference filters, because of their nature, must be used in a collimated beam if they are to function as they are designed. The use of spectral filters permits data to be obtained on the size of particles in the screen sample, and also their color fidelity to be evaluated.

Behind the filter holder is a recollimator which consists of a condensing lens, a second pinhole, and a recollimating lens. This recollimator is used to eliminate stray light introduced into the beam because of scattering and reflection by the filters. It is also useful if additional collimation of the beam is required. Behind the last collimating lens is an iris diaphram to restrict



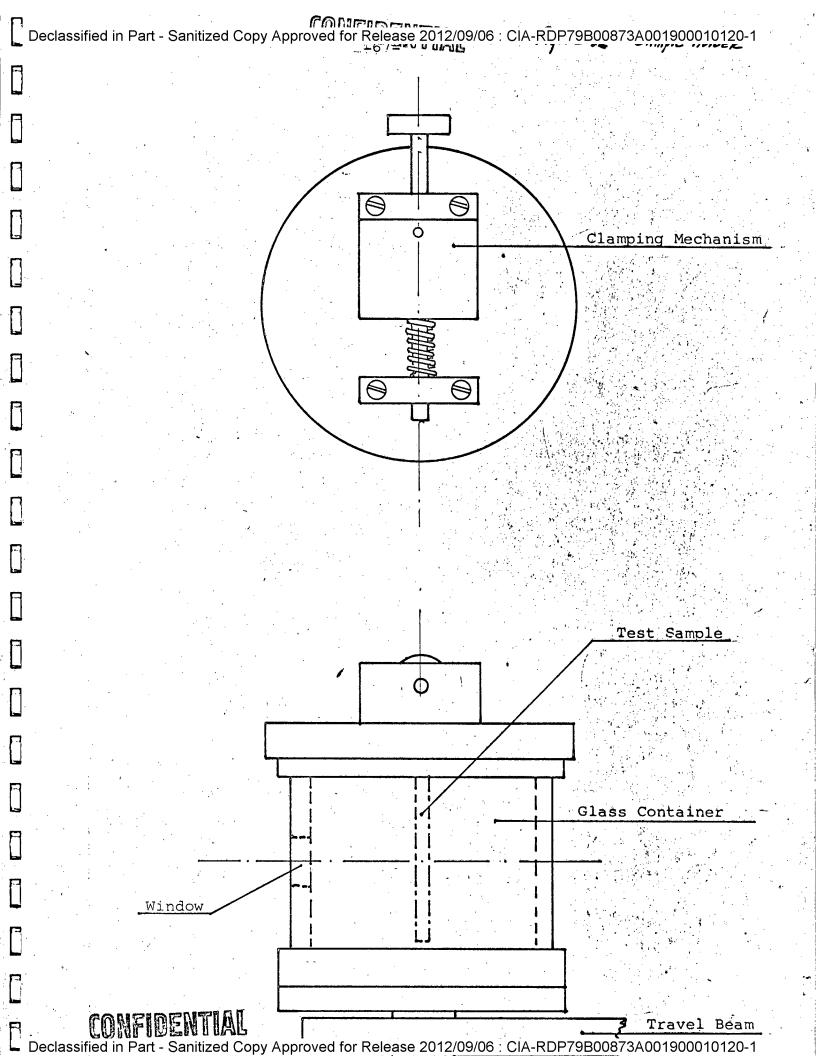
the diameter of the beam. When the recollimator is not being used, it is removed and a second diaghram mounts directly to the filter holder. We have also made provisions to place a monochrometer between the collimator and the sample holder for detailed spectral studies, if this is ever required. All of the lenses throughout, except for the first one in the light source, are identical achromats. They each have a focal length of 65 mm and a clear diameter of 32.5 mm, resulting in a relatively fast f/No. of 2.0.

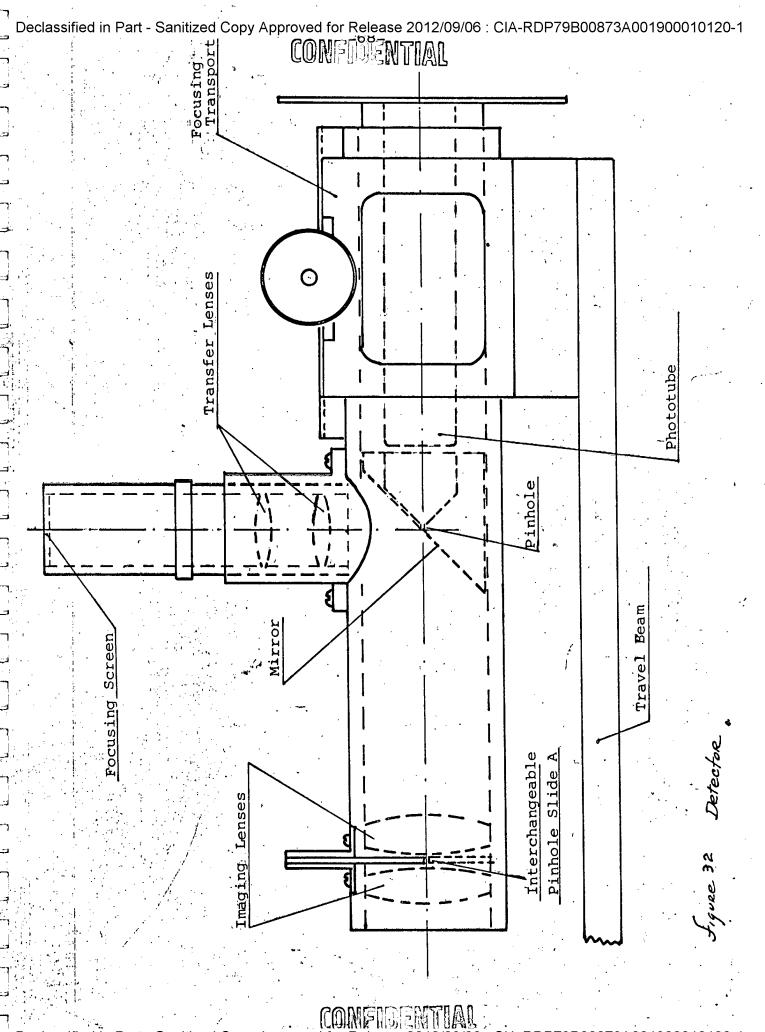
3. Sample Holder

Two different sample holders have been constructed. One consists of a glass cylinder 55 mm high and 69 mm in overall diameter, with a 4 mm wall thickness, Figure 31. Light from the collimating unit enters this cell through a plane window 11 mm in diameter. The cell is filled with a liquid whose refractive index matches that of the glass sample. permits the measurement of the complete scattering function, as no refraction occurs at the glass-liquid interface; hence, none of the light is totally internally reflected and trapped. This cell will be used primarily to verify theoretical considerations. A second sample holder consisting of only a clamp mount will be used to measure the actual viewing properties of screen samples. Both holders have provisions for accurately orienting the sample at $\pm 30^{\circ}$, $\pm 45^{\circ}$, $\pm 60^{\circ}$, and 90° to the incident beam.

4. Detector

The detector unit consists of optical components and a multiplier phototube, Figure 32. Two narrowly spaced achromats focus an image of the object space, i. e., the plane of the sample, onto a specially





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designed aperture. The object space lies in the front focal plane of the first lens. Light from each point in this plane is transformed into a collimated bundle. These bundles make the same angle with the optical axis as does the original source point in the front focal plane. These bundles are brought to focus forming an image in the back focal plane of the second lens. This particular optical configuration permits the distance between the object plane and image plane to be one-half as great as when only a single lens of equal focal length is used.

The special aperture is an aluminized plate inclined 45° to the optical axis. It has a hole in its center of about 1 mm diameter which restricts the origin of the light passing through to a small area on the sample. All of the other light reflects into a small imaging system consisting of two smaller achromats and a small rear view screen. Thus, the light which does not pass through the aperture to the detector is used to form an image of the sample onto the rear view screen. This is used to ensure that the image of the sample is in focus on the pinhole aperture.

A second aperture A, between the first and second lenses, limits the angular size of the cone of light, which the first lens accepts. This is extremely important because even though the optical axis of the detector makes an angle θ with the axis of the collimator, light from a considerably larger angle can enter the system and contribute to the signal. Thus, to ensure a given angular resolution α , an aperture with a diameter d must be inserted between the two lenses.

 $\alpha = d/F$

where F is the focal length of the first lens. Thus, the light beam producing a signal not only originates from a very small area on the sample, but is only a small angular cone of light.

The multiplier phototube is an RCA-7767 having an S-11 response. All of the voltage-dividing network for the tube is located on a circular printed circuit board directly behind it. This complete unit is mounted on a rack and pinion mount which permits accurate focusing on the sample.

5. Control and Display Electronics

The light source that will be used is a highly regulated voltage and current supply driving a 150 watt xenon arc lamp. The detector system is comprised of a small photomultiplier tube. sensitivity of this particular detector will be adjustable by varying the applied voltage between 500 and 1500 volts dc. The dynode voltages are developed across a bleader resistor chain that is adjusted to draw more current than is expected from any one of the dynodes, forcing the dynode voltages to remain constant. By utilizing this type of control, a variable sensitivity over 3 orders of magnitude is obtained. The output of the PM tube is directly coupled into a log converter capable of a 3 decade response without scale changing. This allows compression of the voltage changes over 3 orders of magnitude. The log of the applied voltage from the PM tube (from the log converter) is used to drive the y axis of a Hewlett-Packard x-y recorder.

The PM tube is mounted on a rotating arm so that angular positions from 0° (on the optical axis) to 150° (clockwise rotation) is available for the total scan of the instrument. The angular position is derived from a linear potentiometer mechanically linked to the rotating arm. The span of rotation utilizes a simple "on-off" servo mechanism based on a potentiometric type balance. A similar potentiometer is mounted as a front panel control so that angular rotation is achieved any time there is a difference in the settings of the front panel control and the angular scanning potentiometer associated with the PM tube. The servo, being an 'bn-off" type, monitors merely the difference in the potential between the two potentiometers and controls separate relays for either clockwise or counterclockwise rotations. These relays in turn control a high torque dc motor that provides a constant rotational speed. The angular position potentiometer also provides driving signals to the x axis of the x-y recorder to indicate the exact angle of the PM tube position.

It has been decided to use a combined monitoring system whereby the power supplies of the light source, detector and other control functions, along with the log converter and x-y plotter, will be mounted in one housing to be used for both goniophotometer and the modulation transfer function analyzer. The operating controls for this console will be located on each of the separate test systems. The goniophotometer has a switch for the main power and auxiliary power for controls as well as a detector "on-standby" power control. Parallel cabling between the console and both test systems will allow either one or the other units to be in operation, but not both simultaneously.

B. Modulation Transfer Function Analyzer

Modulation transfer function (MTF) theory has been extensively used to evaluate the resolution of optical systems and components over the last few years. The MTF is a measure of how well the contrast of a particular size detail is transmitted through an optical system as a function of detail size. The measure of detail size is termed spatial frequency, and is the number of cycles of a periodic structure per unit distance. It is denoted by R and has units of cycles/millimeter. As an example, the spatial frequency of the pattern in Figure 33 is 1/X_O cycles/mm.

The contrast, γ , of a sinusoidal intensity distribution, Figure 33, is defined as

$$\gamma = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{(I_{\text{max}} - I_{\text{min}})/2}{(I_{\text{max}} + I_{\text{min}})/2} = \frac{\text{ac amplitude}}{\text{dc level}}.$$

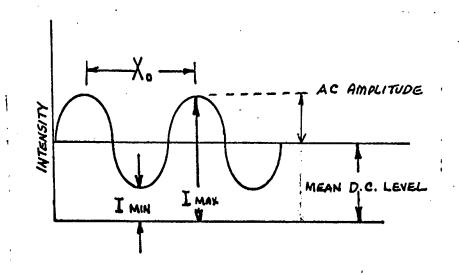


Figure 33. The Physical Meaning of Contrast

It is clear from the above equation and Figure 33 that γ is just the ratio of the ac amplitude to the mean dc level. If $\gamma_i(R_\chi)$ and $\gamma_o(R_\chi)$ are the contrasts of the sinusoidal object and its image respectively, then the modulation transfer function, $T(R_\chi)$, can be defined as

$$T(R_{x}) = \frac{\gamma_{i}(R_{x})}{\gamma_{o}(R_{x})} .$$

Thus, if the MTF is unity at any given value of R, the two contrasts will be the same, meaning no losses occurred in forming an image of that particular size detail. Conversely, if the MTF had been .5, the contrast of the image would be half that of the object. Hence, the MTF is a measure of the loss of information through a system. Usually, only the normalized transfer function is used, i. e., T(0) = 1. It should also be noted that γ_i and γ_o are independent of any absolute power, and γ_i is independent of any uniform attenuation of intensity in the image forming process.

The MTF is a useful parameter to use when arriving at the total performance of a system made up of several components. This is because the effects of each component on the total performance can be considered more simply in this mathematical formalism, as the MTF of a system can be represented as the product of the MTF of each component.

Although many techniques exist for measuring the MTF of a rear projection screen, it seems most logical to measure the MTF under exactly the conditions the screen will be illuminated. This means projecting some type of sinusoidal spatial frequency pattern onto it and measuring the resulting degradation of contrasts by the screen. Such a system is shown in Figure 34. The sine-wave mask consists of a transparency whose transmission is sinusoidal and has a linear increase of

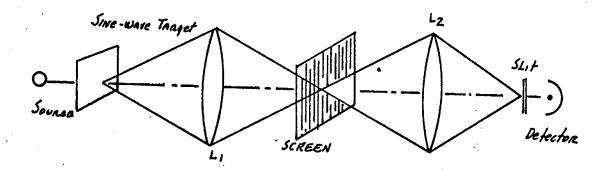


Figure 34 Optical Configuration for MTF Measurements of Rear Projection Screens



Sigure 35 A Typical Sine-Wave Target

spatial frequency with length. A typical pattern is shown in Figure 35.

This is projected onto the sample of rear projection screen material by lens L₁. This image is then relayed to a narrow slit or pinhole by a second lens L₂. As the sine-wave pattern moves across the optical axis, the image will move across the screen and also across the phototube, converting the light intensity into electrical signals. These are then processed with suitable electronics to give the contrast of the image on the screen as a function of spatial frequency. The MTF of only the screen can be obtained by removing the screen and measuring the MTF of just the two lenses. Dividing the MTF of the lenses and the screen by just the MTF of the lenses leaves the resolution characteristics of the screen.

In duplicating a typical projection geometry, the important parameter is the size of the angular cone of light from the lens onto the screen. This can be controlled by appropriately stopping down lens L_1 .

The output from the phototube will look very much like that shown in Figure 36. The dc level will remain constant, with the amplitude of the ac component decreasing with increasing spatial frequency.

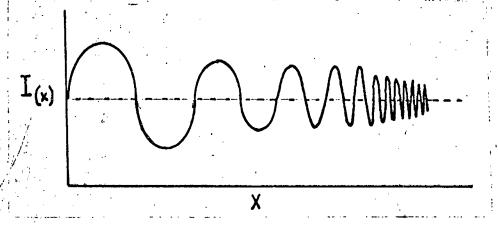


Figure 36. Phototube Output

The signal from the phototube will first be conditioned by means of a unity gain amplifier. This will match the high impedance of the multiplier phototube with the low impedance circuitry which follows. The signal will now be offset by an amount equal to the mean dc level.

After full wave rectification, without filtering, the signal will be presented to the y axis of an x-y plotter. The gain of the y input is so adjusted that when the pattern is at I_{max} of the lowest spatial frequency, the pen moves up to the MTF = 1 line. As the pattern is now scanned across the screen and the pinhole, the plotter will trace out the pattern. The resulting plot is similar to that of Figure 37.

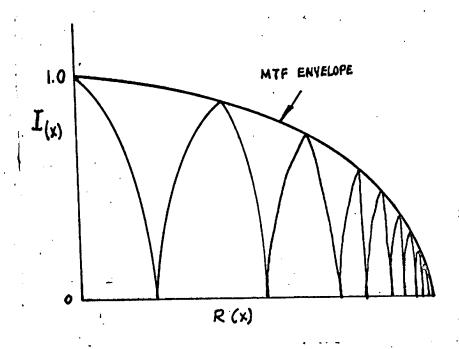


Figure 37. Typical x-y Recorder Trace of the Resolution Pattern

Since the dc level is constant, the contrast of the image is just the height of the envelope across the peaks. This will be measured for the complete system

and then without the screen. Division of the first data by the second gives the MTF of only the screen, independent of any other losses.

The heart of the MTF analyzer is the sine-wave resolution target. The quality of the measurements made with the analyzer are strictly dependent on the quality of the sine-wave target. This target must not have over a few per cent harmonic distortion if the sine-wave MTF is to be useful and meaningful. It must also maintain both a constant dc level and a constant contrast, and be strictly linear in spatial frequency. Simple sine-wave patterns of constant spatial frequency are available, but they cannot be used and are very expensive. Unfortunately, resolution targets with a continuous variation in spatial frequency cannot be obtained; for this reason, we are making our own.

One technique to make these resolution masks consisted of using a long arm Michelson interferometer to generate interference patterns which were then recorded on film, Figure 38. From this many problems became evident. First, the intensity distribution from the

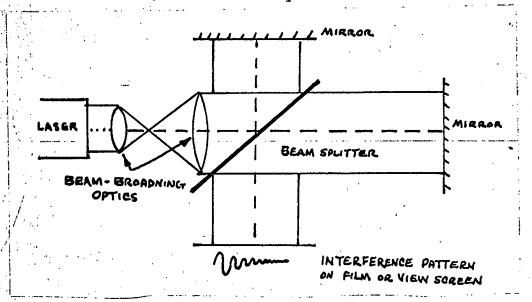


Figure 38. Optics of the Michelson Interferometer



laser is not uniform but Gaussian, and considerable expansion of the beam is necessary to get a usable portion of it which is uniformly bright. Some of the advantages gained by using a laser source, i. e., ease of alignment and long coherence length, are apparently lost because of diffraction patterns introduced by apertures, shutters, and specks of dust in the system.

These problems become quite serious for interferometers with long arms because of the large size of the diffraction images. A very short arm Michelson interferometer has been constructed to test this approach further. It is hoped the short arms will keep the unwanted diffraction patterns very small. The resulting sine-wave patterns will be about 30 mm square.

Another way of making such masks is to draw the film past a slit which is being illuminated by a sinusoidally modulated light beam. The modulation can be produced by a wide variety of techniques. This may be done by modulating either the light source directly or the beam after leaving the source. However, it is usually very difficult to accurately modulate any light source.

Because Tungsten lamps change their color temperature over a modulation cycle, and since they have severe frequency response limitation because of the finite heating and cooling time of the filament, they are of no value. This is not the case with xenon lamps, but the size and position of the plasma ball changes with power levels, particularly when the power drops to almost the threshold level. This also occurs for neon lamps and gas-lasers modulated through their power supply.

A better and more practical approach is to modulate the beam after it leaves the source. Electro-optical crystals such as KDP can be used very effectively. Unfortunately, they require several thousand volts to modulate, but this is not an insurmountable restriction.

A very simple modulator can be made by rotating a polarizing material in a beam of linearly polarized light, Figure 39. The intensity $I(\theta)$ through the material, as a function of the angle between the electric field of the beam and the transmission axis of the material, is

$$I(\theta) = K I_{o}(1 + \cos \theta) .$$

Here $\mathbf{I}_{\mathbf{O}}$ is the incident intensity and K is a constant which accounts for the density of the polarizer,

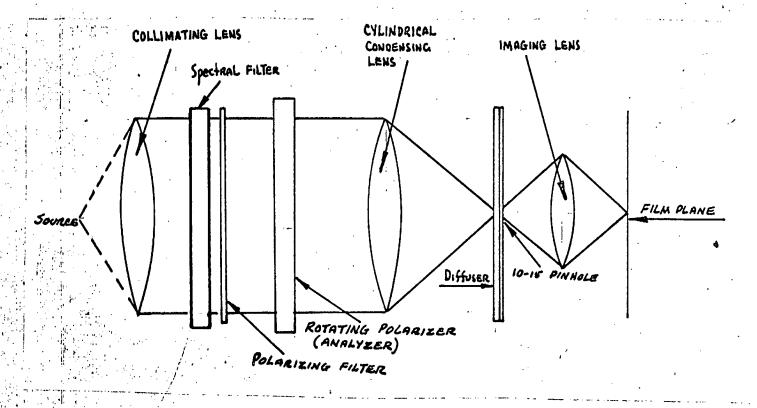


Figure 39. Optics for the Sine-Wave Target Generator

regardless of polarization. It should be remembered that the angle θ can only extend to 90° , as a rotation of 120° is equivalent to a θ of 60° . Consequently, a full rotation of the polarizing material causes two complete cycles of modulation. Thus, if ϕ is the phase angle of the modulation, $\phi = 2\theta$. This approach—making the special sine—wave resolution target—will run parallel with the interferometer work just described.

When the polarizers are so rotated to be most opaque, their spectral transmittance changes leaving a transmission window in the blue. To prevent this from introducing nonlinear modulation of the beam, the spectral distribution of light from the xenon source will be limited by an interference filter which peaks in the green portion of the spectrum. The cylindrical lens focuses the collimated beam onto the opal glass which diffusely illuminates the 10-15 micron slit. This is then imaged onto the film in a transport by a high quality lens. The spatial frequency R_x, obtained in this way, is given by

$$R_{x} = \frac{2F}{V}$$

where F is the frequency of rotation of the analyzer in cycles/sec., and V is the speed of the film in the transport in mm/sec. A sine-wave pattern made in this way will have a continuously variable frequency from .2 to 10 cycles/mm; hence, for a constant speed of V = 1 mm/sec requires F to vary from .1 to 5 revolutions/sec. This pattern will be demagnified 5 times in the MTF analyzer giving spatial frequencies from 1 to 50 cycles/mm.

The film is of particular importance because it must record all of the spatial information without loss of

contrast. The film chosen for this is Kodak Type S0-243, a high resolution aerial film. It has an ASA speed of 1.6, and as can be seen from the MTF data for this film, Figure 40, its response is essentially flat to 10 cycles/mm and good beyond 250 lines/mm.

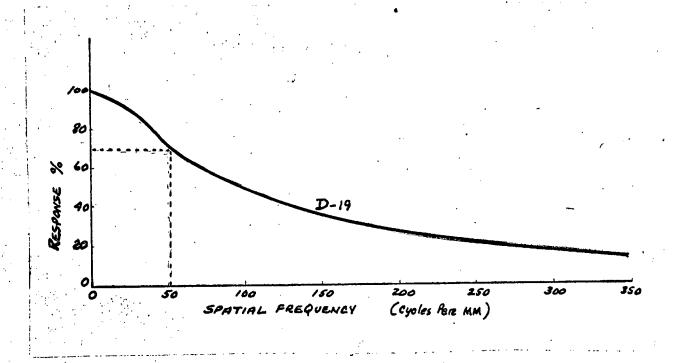


Figure 40. MTF of Kodak Film Type S0-243

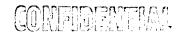
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VII. Data Appendices

An IBM model 1620 digital computer with a 20K memory was used to compute all the necessary light scattering func-The computer programs were written using Fortran language and compiled with the PDQ-Fortran processor. The scattering functions $I_{\ell\ell}(\theta)$, $I_{\perp}(\theta)$, $Gain(\theta)$, EFF and the per cent polarization were first computed using the program "MIE-III". The compressed data of only Gain θ appear as Appendix A. These raw data were then corrected for refraction at the air glass interface and for reflection losses by the program "MIE-S3". efficiency functions indicating the fraction of the incident light which was backscattered EBU, trapped by total internal reflection, ETU, and which actually passed through the screen to the viewers, EFU, were also computed. The corrected data, Gain (θ) , are presented in Appendix B.

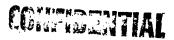
Because the function, Gain (θ) , and the efficiency functions are the most important single data, they were separated from all the other data of the first two programs by a third program "MIE-Compressor". This program compressed the data into the form in which it appears in Appendices A and B. A list of these programs constitute Appendix C.

All of the data were printed directly onto "Ditto" masters by the computer saving considerable time and reducing the chances of human errors during transcription. It should be noted that since the greek symbol α , used to designate particle size, was not available on the printer the letter "A" was substituted. Also because no data was computed for $\alpha = 7$ and 9 at M = 1.20, zero's appear in the computer data at these values. It should be remembered that the data, $Gain (\theta)$, is not strictly valid beyond $\alpha = 5$; however, for α greater than 5 the shape of the $Gain (\theta)$ curves still give some measure of the increase in the directivity with the particle size parameter α .

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APPENDIX A Raw Data



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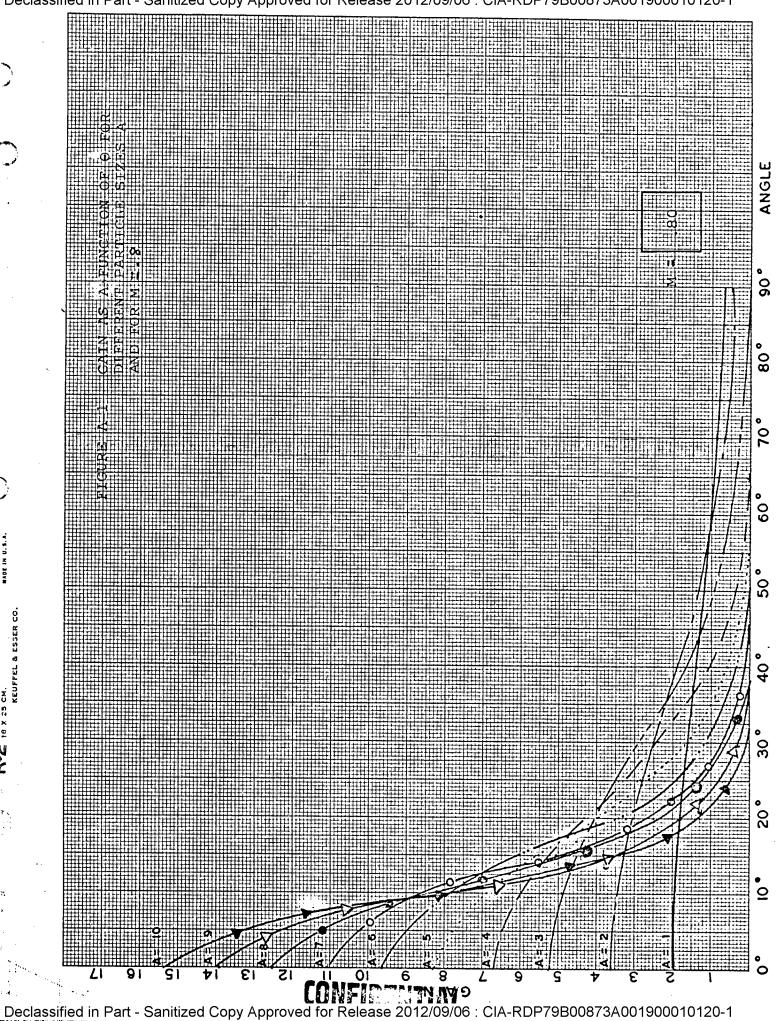
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	2	5.	1.90	3.57	5.16	6.53	7.86	9.11	10.28	11.34	12.30	13.12
	3	10 e	1.87	3.47	4 6 9 0	600 i	6.96	7.69	8.19	8.45	8.46	8.21
	4	15 a	1.82	3,30	4.49	5.23	5.67	5.77	5,58	5.12	4.47	3.73
	5	20.	1.76	3.08	3,97	4.30	4.25	3.84	3.22	2.51	1.85	1.36
\sqcup	, 6	25,	1.67	2.81	3.40	3.34	2.92	2.25	1.57	1.03	.72	.64
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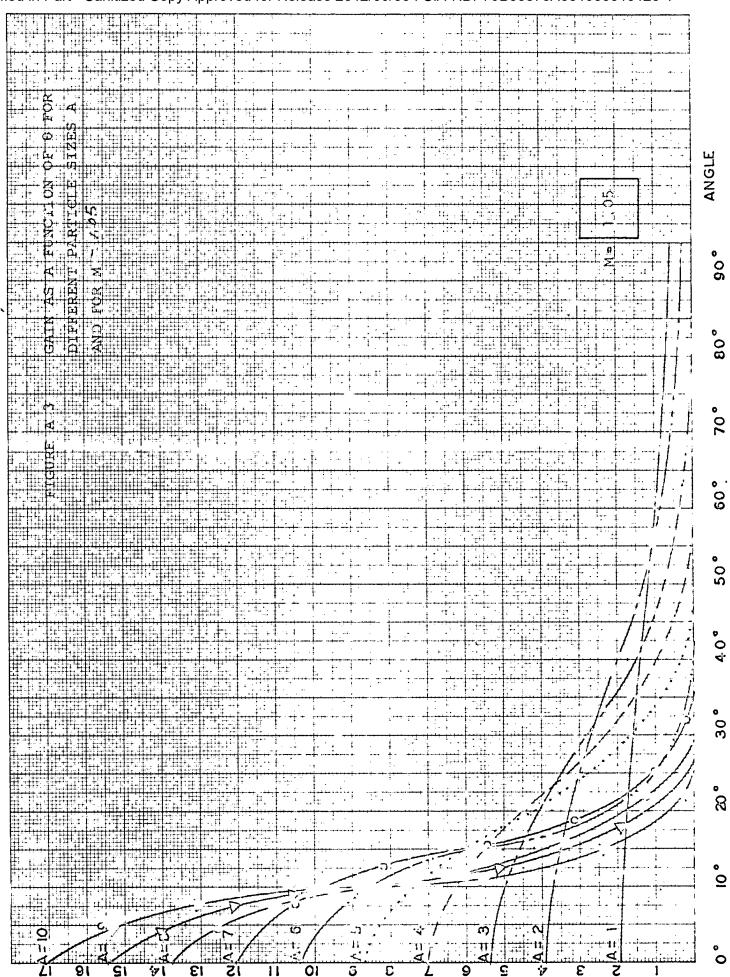
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	3	10 e	1.88	3,65	5.00	6.27	7.31	8.11	8.66	8,92	8.92	8.67	
	4	15.	1.84	3.48	4.58	5.43	5.87	5.92	5.61	5.02	4.22	3,32	
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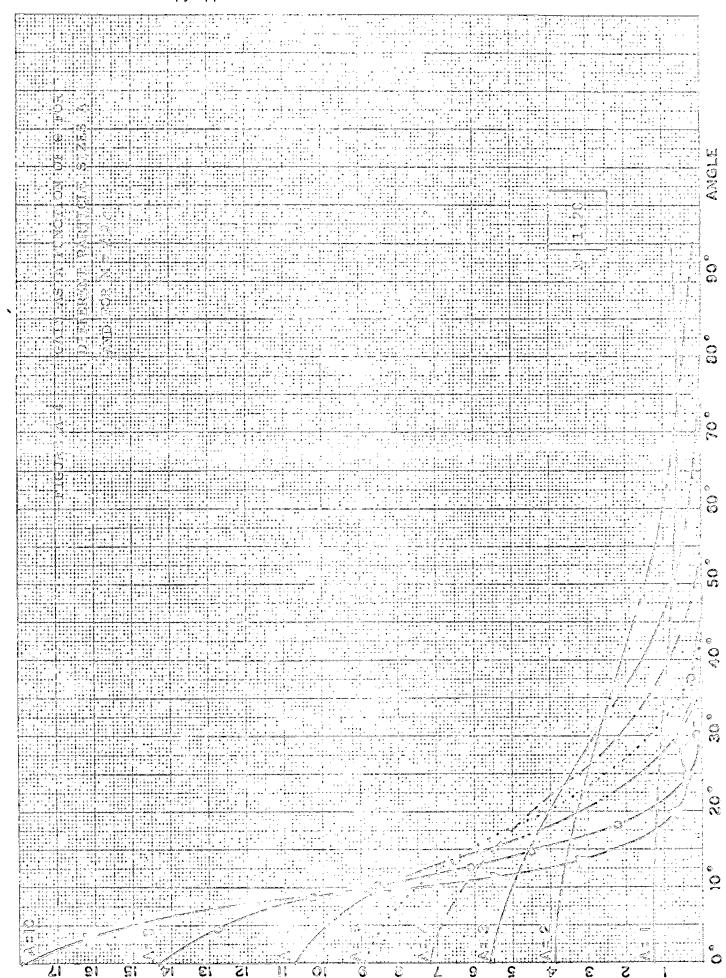
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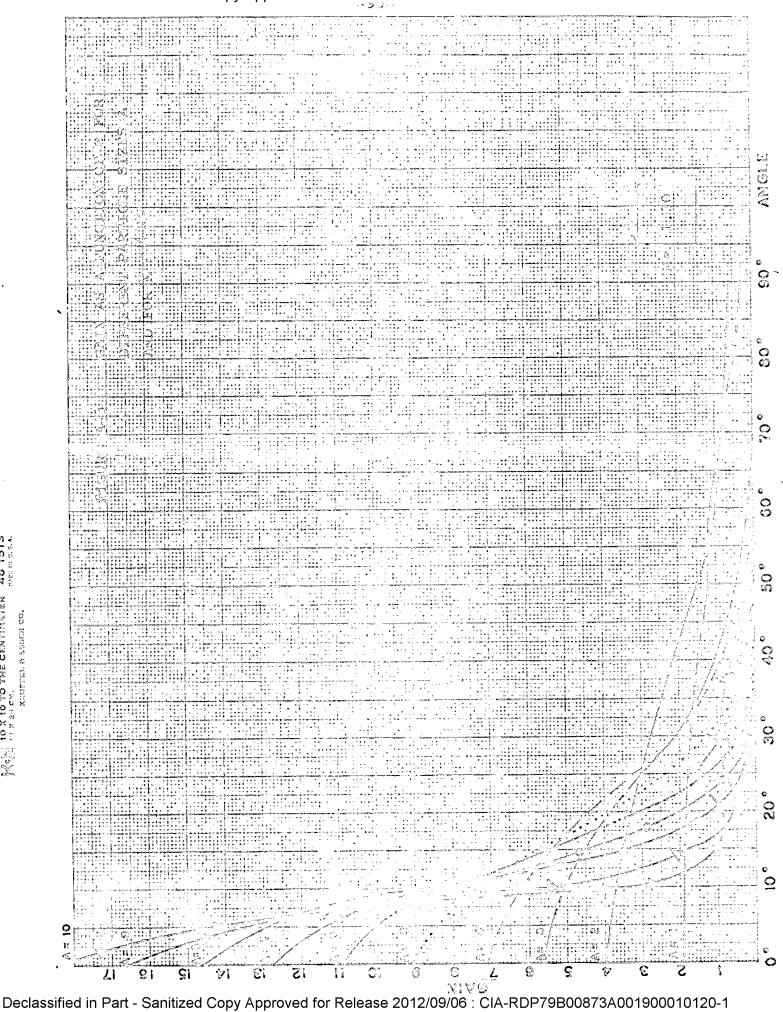


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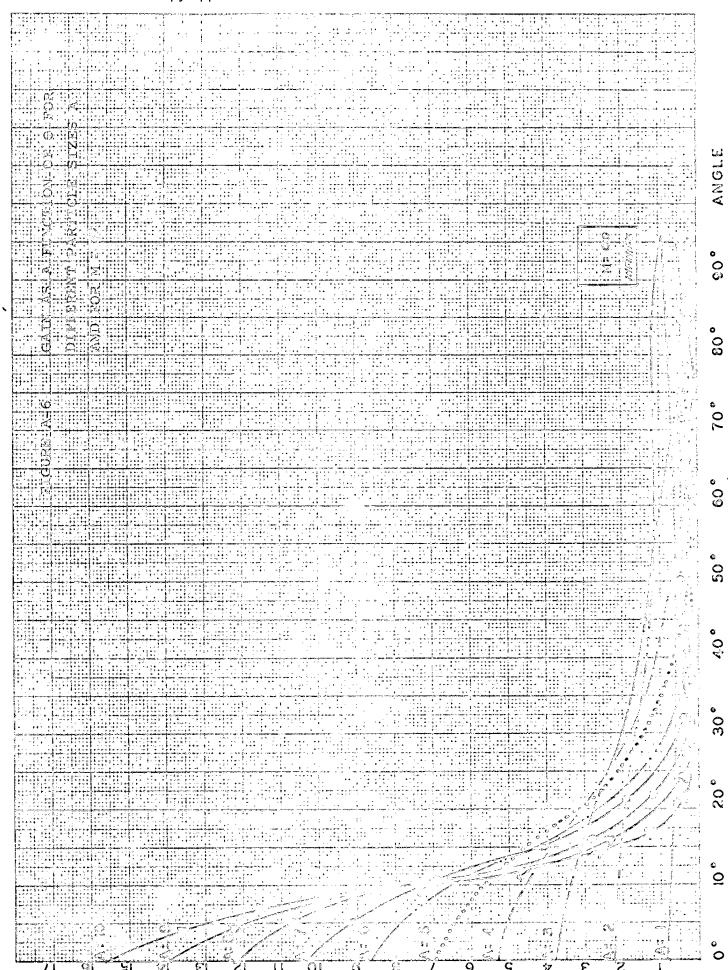
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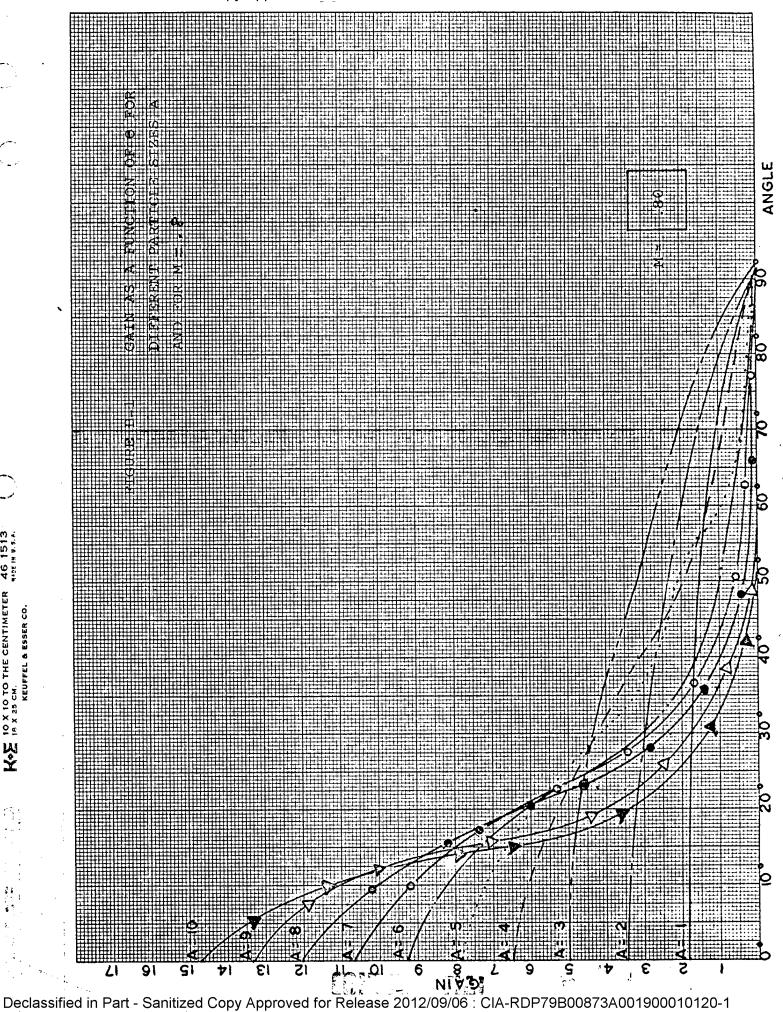
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	된 경험을 되었다. 현실 전에 보는 사람들이 되었다. 1902년 - 1908년
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	4	22 .8	1.75	3.16	4.30	5.02	5 ₀ 44	5.54	5。35	4.91	4.29	3 ₀ 57
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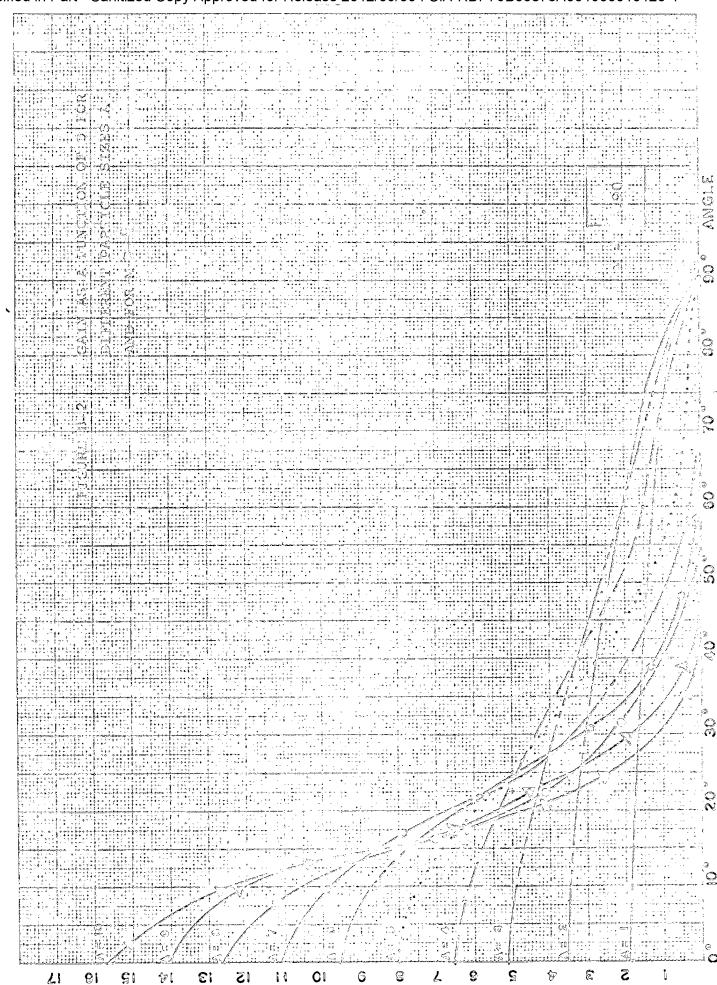
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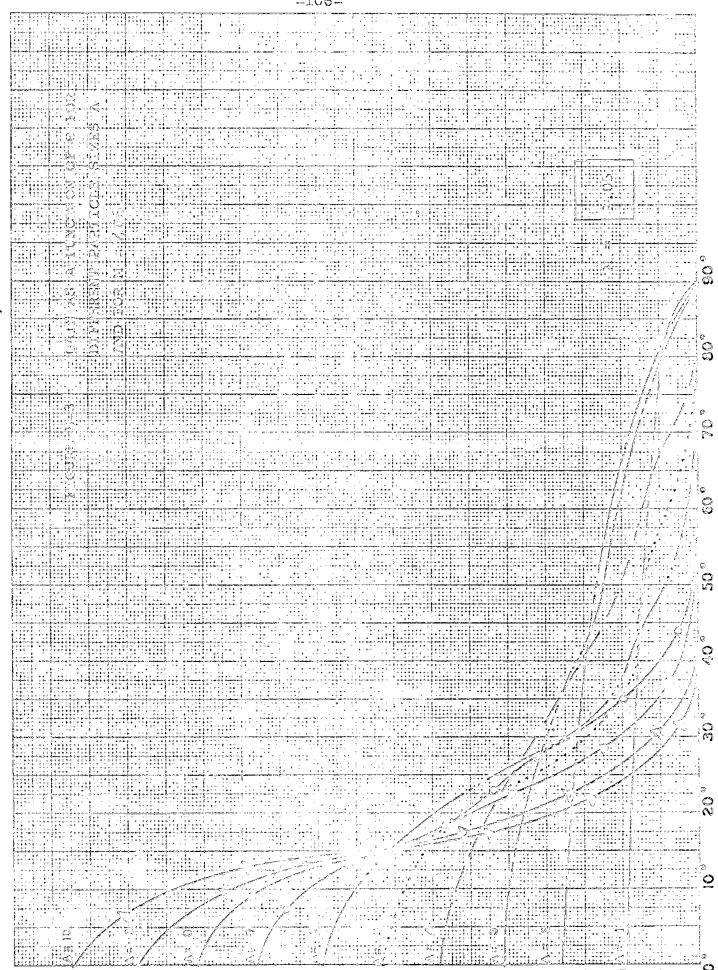
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	2	7.5	1 .84	3,61	5.06	6,56	7.98	9 _e 35	10,65	11.85	12,94	13.93
_	3	15.0	1.81	3,50	4.80	6.02	7.01	7.78	8.31	8.56	8.56	8 _e 32
	4	22.8	1 . 76	3,33	4.39	5.21	5.63	5,68	5。39	4.81	4.05	3.19
	5	30,8	1.69	3.11	3,88	4.23	4.09	3.57	2.79	1 0 95	1.17	¢58
	6	39.3	1.61	2.83	3.29	3,22	2.66	1.87	1 = 07	·46	.12	.02
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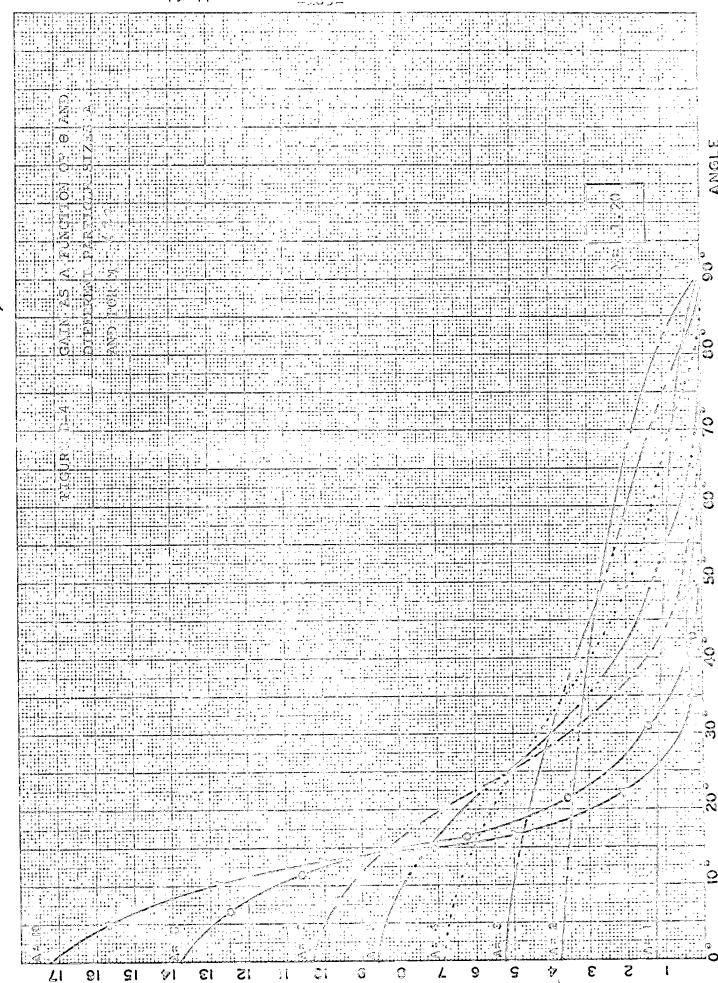


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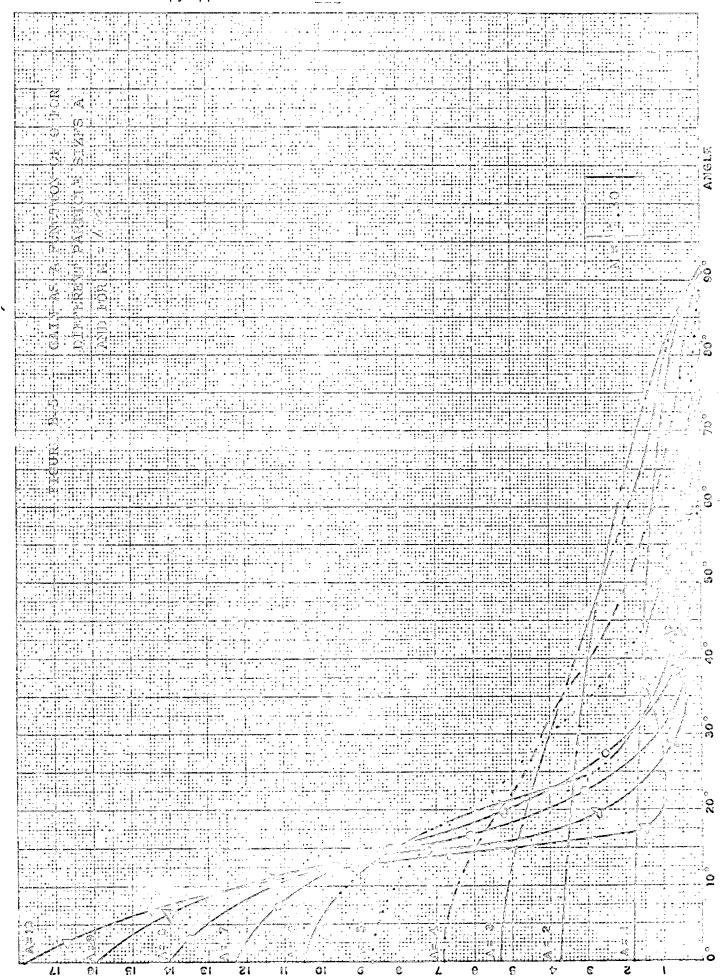
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	ŧ	•		ANG	JLAR GA	IN FUNCT	TIONS F	OR M =	1.20				
		THETA	A=1	A=2	A=3	A=4	A=5	A=6	A=7	A=8	A=9	A=10	
	1.	0	1.22	3073	5.24	6 ₀ 89	8。59	10.30	٥٥٥	13.75	.00	17.26	
	2	7.5	1.22	3.69	5,15	6,68	8.20	9.64	.00	12,19	٥٥٥	14017	
	3	15.0	1.20	3.59	4.87	6.10	7.13	7.87	000	8.38	000	7.57	
	4	22.8	1.16	3.41	4045	5,23	5.61	5.54	.00	4.29	٥٥٥	2.34	
	5	30.8	1.12	3.18	3.91	4.20	3,96	3,30	٥٥0	1.50	00ء	۰45	
	6	39 _° 3	1.06	2.90	3.30	3.13	2.48	1.59	00	.34	o.00	٥40	
	7	48.5	۰98	2,58	2.65	2.15	1.33	•58	٥٥٥	.17	000	041	
	8	59.3	88	2.18	2.00	1.32	۶58 a	.16	ó 0 0	.22	.00	.16	
-	9.	74.6	65ء	1.52	1.21	ه62	.17	•06	e O O	.15	000	003	
	ĩ O	105.3	°86	.00	.02	.01	۰00	٥٥٠	000	o O O	٥٥٥	.00	
	1.1	120.6	1010	٥٥٥	e03	0 O I	00 د	۰00	٥٥٥	o O O	•00	٥٥٥	
_	12	131.4	1018	。00	۰03	002	a O O	°00	٥٥٥	000	٥00	•00	
	13	140.6	1.23	000	٤٥٥	02ء	。00	٥00	. 00	000	000	٥٥٥	
	4	14901	1.27	۰00	033	<u>002</u>	001	۰00	۰00	٥00	o 0 0	e O O	
	15	157.1	1 30	٥٥٥	003	。03	.01	٥٥٥	٥00	ø 0 0	000	.00	
U	16	164.9	1,31	.00	٤٥.	٤0،	o 0 1	900	٥00	٥00	00	.00	
	17	17204	1.32	۵00	٥03	٥03	.01	۰00	o 0 0	000	٥٥٥	.00	
	18	180.0	1.33	٥00	003	603	02،	•00	٥00	.00	.00	٥٥٥	
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		ì		<u> </u>	
		EFFICIEN	CY FUNCTIONS FOR	M = 1.20	
P	Á	EFU	ETU	EBU	
Ц	1	o2419	ه 4799	٠2780	
	2	6801	.3179	.0018	
	3	08281	01642	.0076	,
U	4	9087	0848	ە0063	
	5	o9 370	。0603	÷0025	
M	6	.9419	。0571	。0009	
L	7	0000	.0000	.0000	
	8	。9472	o0517	.0010	
	9	a 0000	٥٥٥٥ و ٥٥٥٥	.0000	
	10	o9497	₀ 0495	。0007	
	•				•
	4				. 5
470					

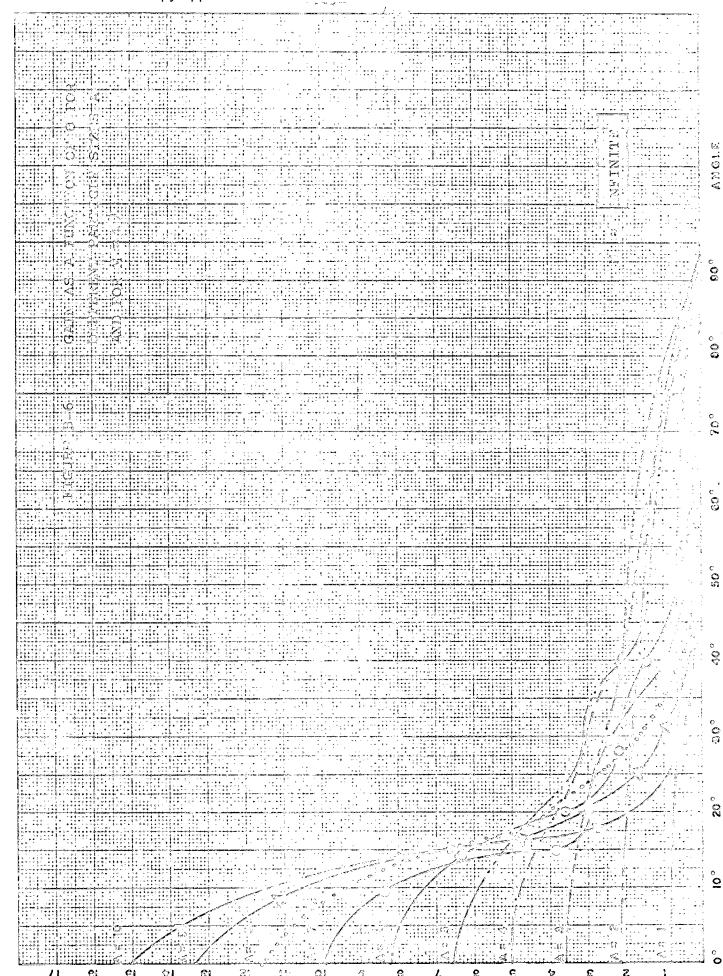
L				-			•		•			1
				·								•
				ANG	JLAR GA	IN FUNC	TIONS F	OR M =	1.30			
A		THETA	A=1	A=2	A=3	A=4	A=5	A=6	A=7	A=8	A=9	A=10
	1	, 0	1.87	3.73	5,33	6.79	8,74	10.48	12.25	14.04	15.90	17,85
	2	7.5	1 .86	3.70	5,23	6.59	8.31	9,75	11.06	12.20	13,09	13,59
	3	15.0	1.84	3,59	4,94	6.01	7.15	7-082	8.09	7.88	7.06	5.49
	4	22.8	1.79	3,42	4.50	5.15	5.53	5。33	4.66	3,59	2.24	۰93
	5	30.8	1.72	3.19	3,94	4.13	3.81	3.02	2,02	1.10	。60	•88
Fi	6	39,3	1.64	2,92	3.31	3.07	2,29	1.36	e 65	•42	e78	1 . 48
	7	48,5	1.52	2.59	2.54	2.10	1.17	•48	•27	ه 51	.87	.92
	- 8	59.3	1.37	2,20	1.97	1.28	o49	.19	930	e 5 1	o 49	ه31
-	9	74.6	1.02	1 , 55	1019	ø60 [°]	o16	014	.27	e 26	.16	e24
	10	105,3	e49	9 O O	o O 1	•02	9 O I	e O 1	ø00	a O î	•03	٤0.6
	11	120.6	_e 64	.01	00 î	s 0 3	°05	ø01	.01	ø O O	•02	۰05
F	12	131.4	68ء	e O 1	.01	ø 03	002	•02	٥02	.01	.01	٥02
	13	140.6	671	o O 1	.01	•03	°02	•02	•02	۰03	٥03	.02
	14	149.1	673	ø02	002	004	02	002	•02	٥03	۰05	.07
	15	157.1	674	•02	002	₉ 06	.02	001	.01	٥02	₀ 04	₀ 08
	16	164.9	ه 75	÷02	002	.07	002	•02	e O 1	000	001	ø04
	17	172.4	₃ 76	٥03	.02	80 €	٥03	002	& O &	.00	۰00 -	۶0°
	18	180.0	ه 76	ОЗ	*02	800	.03	\$02	ø 0 1	٥O o	.01	o 0 4
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		EFFICIENCY	FUNCTIONS FO	R M = 1.30	-
— 	A	EFÜ	ETU	EBU	
	1	o 3725	o4675	o 1599	
	2	o682 7	.3124	٥0048	
7	3	e8348	01604	۰0047	
Ц	4	。 8938	。0940	•0120	
	5	o 9242	a 0699	۰0058	
<u>-</u>	6	۰9259	。0693	。0047	
	7	e9278	。0684	.0037	
	8	₉ 9289	.0671	0039	
7	9	° 922 9	.0707	c 0 0 6 2	
Ŭ ,	10	9092	.0798	.0109	
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				ANGL	JLAR GA	IN FUNCT	rions fo)R M =	Infini	te		÷
一. 同		THETA	A=1	A=2	A=3	A=4	A=5	A=6	A=7	A=8	A=9	A=10
	1	ø 0	e73	2.12	3.58	5.07	6.64	8.27	9.95	11.65	13,35	15.06
	2	7.5	ه73	2,09	3,50	4 , 90	6,29	7,67	8 • 99	10.22	11.33	12.30
_	3	15.0	a72	2003	3, 29	4,41	5.37	6.13	6.65	6.90	6.89	6.63
	4	22.8	.71	1 . 92	2,97	3.73	4.17	4.28	4.08	3,63	3.01	2.33
	5	30.8	. 69	1,80	2,61	3.01	3,02	2.69	2.16	1.56	1.00	•5 9
_	6	39,3	•66	1,65	2.25	2.36	2.09	1 59	1.05	ø60°	• 33	₀ 24
	7	48.5	•62	1.50	1,92	1.84	1.43	o 9 1	₀ 48	_a 25	ø21	_® 29
	8	59 ₀ 3	57	1.34	1.62	1,42	₉ 95	o47	•21	• 19	_@ 30	, 34
	9	74.6	.43	1.02	1.21	•96	.51	.18	.13	25	» 28	81 e
	10	105.3	1.05	•21	o 31	• 25	.15	.15	,16	e 12	011	011
	11	120.6	1.34	•26	。32	.31	ø20	.17	.19	. 1 6	•13	.13
=	12	131,4	1.44	, 29	, 28	•31	•23	.17	.18	•18	e 15	.13
	13	140.6	1.49	_e 32	o 24	•30	.25	.19	.17	.18	·16	a 1 3
	14	14901	1.53	₀ 35	₀ 21	.27	₂ 26	.21	.17	.17	•16	.14
— —	15	157.1	1.56	,37	,19	.25	e27	•23	.18	a 16	· 15	.14
	16	164.9	1.58	°39	e 18	.23	.27	.25	•19	°15	• 14	e 1 4
	17	172.4	1.59	o 4 0	.17	•22	.27	•26	.21	• 15	.13	.13
	18	180.0	1.59	o41	₀ 17	.21	.27	•27	321	.15	•13	,13



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				,		
		EFFICIENC	Y FUNCTIONS FOR	M = INFINITE		
	, A	EFU	ETU	EBU		
	, 1	. 1499	e5146	。3353		٠
П	2	₀ 3926	₀ 5303	.0770		
<u>-</u>	. 3	•5763	_e 3676	°0539		
	4	₉ 6920	.2467	e0612		
	5	o7507	61928·	÷0563		.
	6	。7790	.1722	。0486		
L	7	。7977	.1593	.0428		
	8	o8159	o 1466	o 0374		
-	9	。832 5	61340	60333	: •	
	10	o8446	.1241	.0312		
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			ing the Agent of the Company of the
	APPENDIX C		
	Computer Progr	rams	
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	CONFIDENT		

```
COMPARATOR
Declassified in Part - Sanitized Copy Approved for Release 2012/09/06: CIA-RDP79B00873A001900010120-1
                                    ...8 <u>i</u>. i. e...
       PROGRAM
                  MIE
                         SOLUTION
                                                                BRUCE HERRICK X 333
       A = REAL PART OF AN
       B = IMAGINARY PART OF AN
000
       C = REAL PART OF BN
       D = IMAGINARY PART OF BN
       Y = FIRST DERIVATIVE OF THE LEGENDRE POLYNOMIAL
C
C
C
       Z = A FUNCTION OF THE SECOND DERIVATIVE OF THE LEGENDRE POLYNOMIAL
       P = TITLE
       NCOF = NUMBER OF CARDS NEEDED TO INPUT TABLE OF AN AND BN
000
       INST = STARTING ANGLE
       INSP = LARGEST ANGLE
       IDEL = INCREMENT IN ANGLE
C
       DIMENSION A(50), B(50), C(50), D(50), P(16), R(37), S(37), T(37), POL(37)
       IF (SENSE SWITCH 01) 290, 45
       READ 50, NCOF
45
50
       FORMAT(13)
65
       DO 100 I = 1, NCDF
       READ 70, ICHK, A(I), B(I), C(I), D(I)
       FORMAT(13, 1X, F9.6, 1X, F9.6, 1X, F9.6, 1X, F9.6)
       IF(I - ICHK) 80, 100, 80
80
       CONTROL 102
       TYPE 85, I
_85
       FORMAT(8HCARD NO.: 15, 1X, 35HOUT OF ORDER ** CORRECT AND RELOAD ,
      115HLAST DATA BLOCK)
       PAUSE
       GO TO 40
100
       CONTINUE
BEGIN TRACE
       CONV = 3.14159 / 180.
140
       READ 150, P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(8),P(9),P(10),
      1P(11),P(12),P(13),P(14),P(15),P(16)
       BEGIN PROCEEDURE 1
       CONTROL 971
       PRINT150, P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(6),P(9),P(10),
      1P(11),P(12),P(13),P(14),P(15),P(16)
       PUNCH150, P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(8),P(9),P(10),
      1P(11),P(12),P(13),P(14),P(15),P(16)
       PUNCH 145
       PUNCH 145
       PUNCH 145
       FORMAT(1X)
       END PROCEEDURE 1
 150
       FORMAT(16A5)
       READ 160, INST, INSP, IDEL
160
       FORMAT(313)
       ADEL = IDEL
       BEGIN PROCEDURE 2
       PRINT 170
170
       FORMAT (
                  6X,5HANGLE, 3X, 11HINTENSITY 1,4X, 11HINTENSITY 2,4X,
      111HINTENSITY 3, 5X, 4HGAIN, 6X, 7HPERCENT)
180
       FORMAT(5X, 7HDEGREES, 4X, 6HNORMAL, 8X, 8HPARALLEL, 6X)
      111HUNPOLARIZED, 3X: 8HFUNCTION, 2X: 12HPOLARIZATION)
      PUNCH 170
       PUNCH 180
```

```
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                                                -CV I IML
                                          _119_
       PUNCH 145
       CONTROL 951
       END PROCEDURE 2
       NUM = (INSP - INST) / IDEL + 1
       SUMT = 0.0
       DO 280 I = 1, NUM
       XX = (I - I) * IDEL + INST
       X = COS(XX * CONV)
       E = 0.0
       F = 0.0
       G = 0.0
       H = 0.0
       DO 240 J = 10 NCOF
       L = LA
       IF(J - 2) 200, 210, 215
       Y = 1.00
       Z = X
       GO TO 230
       X \approx 0.6E = Y
       Z = 6.0 * X * X - 3.0
       GO TO 230
       IF(J - 3) 220, 220, 225
220
       V1 = Y
       W1 = 3.0
       W = 15 . * X
       Y = 7.5 * X * X - 1.5
       Z = X * Y \sim (1.0 - X * X) * 15. * X
       GO TO 230
225
       V2 = V1
       V1 = Y
       Y = X * (2.0 * AJ - 1.0) * V1 / (AJ - 1.0) - AJ / (AJ - 1.0) * V2
       W2 = W1
       Wi = W
       SW+1V*(0.1-LA*0.5)=W
       Z=X*Y-(1,0-X*X)*V
       E = E + A(J) * Y + C(J) * Z
       F = F + B(J) * Y + D(J) * Z
       G = G + A(J) * Z + C(J) * Y
       H = H + B(J) * Z + D(J) * Y
       CONTINUE
       R(I) = E * E + F * F
       S(I) = G * G + H + H
       T(I) = (R(I) + S(I)) / 2.0
       SUMT = SUMT + T(I)
      POL(I) = (R(I) - S(I)) / (R(I) + S(I)) * 100.
280
      CONTINUE
END TRACE
      SUMT = SUMT - (T(1) + T(NUM)) / 2.0
       QT = 0.0
       N = NUM - 1
      K = 90 / IDEL + 1
       GO TO 309
290
      READ 291. NUM. N. K
291
      FORMAT(312)
       READ 150, P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(8),P(9),P(10),
     1P(11) oP(12) oP(13) oP(14) oP(15) oP(16)
      READ 292
```

```
Declassified in Part - Sanitized Copy Approved for Release 2012/09/06: CIA-RDP79B00873A001900010120-1
                                  FAIM THEN IN HAL
      FORMAT(1X)
      DO 305 I = 1, 37
      READ 294, J, XX, R(I), S(I), T(I), POL(I)
      FORMAT(14, 2X, F5,0, 4X, E13,6, 4X, E13,6, 4X, E13,6, 6X, F8,3)
      IF(I - J) 295, 305, 295
      CONTROL 102
      TYPE 85. I
      PAUSE
      GO TO 40
      CONTINUE
      READ 292
      SUMT = 0.0
      DO 308 I = 1, N
      SUMT = SUMT + (T(1) + T(1 + 1)) / 2.0
      CONTINUE
      QT = 0.0
      DO 310 I = K_{\bullet} N
      QT = QT + (T(1) + T(1 + 1)) / 2.0
      CONTINUE
      QT = QT / SUMT
      EXECUTE PROCEEDURE 1
      CONTROL 951
      PRINT 315, QT
      PUNCH 315, QT
      FORMAT(30X, 13HEFFICIENCY = , F6.4)
      PUNCH 145
      PUNCH 145
      PUNCH 145
      CONTROL 951
      EXECUTE PROCEDURE 2
      V = 180. / ADEL
      DO 400 I = 1, NUM
      ZT = T(I) / SUMT * V
      XX = (I - 1) * IDEL + INST
      PRINT 320, I, XX, R(I), S(I), T(I), ZT, POL(I)
      PUNCH 320, I, XX, R(I), S(I), T(I), ZT, POL(I)
      FORMAT(14,1X,F5,0,2X,E13,6,2X,E13,6,2X,E13,6,2X,F7,3,4X,F8,3)
400
      CONTINUE
      GD TO 40
      END
```

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                                                                                                  A CAR DE SERVICE DE SE
                    PROGRAM
                                               MIE
                                                                                                                                                                          BRUCE HERRICK X 333
                   DO 12 1 = 10 9
  5
                   READ 10, K. SS(1), TIN(1), TIP(1)
                   DIMENSION A(40), B(40), C(20), P(16), SS(20), TIN(9), T1P(9)
                    FORMAT(13, 30X, E13.6, 3X, E14.7, 3X, E14.7)
   10
                   IF(I - K) 11, 12, 11
                    TYPE 108. I
                   PAUSE
                   GO TO 5
                   CONTINUE
                   DO 15 I = 1, 9
                   L = I + 9
                   J = 10 - I
                   SS(L) = 180 - SS(J)
                   CONTINUE
                   CONTROL 971
                   AN = 2.5
  20
                   SUMC = 0.0
                   READ 25 , P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(8),P(9),P(10),
                 1P(11) .P(12) .P(13) .P(14) .P(15) .P(16)
                   FORMAT(16A5)
                   DO 30 I = 1, 10
                   READ 28
                   FORMAT(3X)
                   CONTINUE
                   CS = 0.0
                   DO 110 I = 1, 37
                   READ 100, J, XX
                                                                    o A(I)o B(I)o CT
                   IF(I = 1) 90, 90, 95
                  SU = CT / 2.0
95
                   CONTINUE
  100
                  FORMAT(14,1X,F5,0,2X,E13,6,2X,E13,6,2X,E13,6)
                   SUMC = SUMC + CT / 2.0 + CS / 2.0
                  CS = CT
                   IF(I - J) 105, 110, 105
  105
                   CONTROL 102
                  TYPE 108, 1
  108
                  FORMAT(8HCARD NO., 15, 1X, 33HOUT OF ORDER CORRECT AND RELOAD,
                115HLAST DATA BLOCK)
                  PAUSE
                  GO TO 20
 110
                  CONTINUE
  BEGIN TRACE
                  SUMC = SUMC - SU
                  CONV = 3.14159265 / 180.0
                  CONVS = CONV * 5.0
                  PI = 3.14159265
                  SUMC = SUMC * CONV5
                  DC 140 I = 1, 9
                  A(I) = A(I) * TIN(I)
                  B(I) = B(I) * TlP(I)
                  C(I) = (A(I) + B(I)) / 2.0
  140
                  CONTINUE
                  DO 150 K = 1, 9
                   I = K + 28
                  J = 10 = K
                  L = 9 + K
```

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                                   LOWETH SERVING
      A(L) = A(I) * T1N(J)
      B(L) = B(I) * T1P(J)
      C(L) = (A(L) + B(L)) / 2.0
      CONTINUE
160
      AK = .01584811
      EBU = C(9) * AK / SUMC
      00 170 I = 1, 8
      EBU = EBU + (C(I) + C(I + 1)) / 2.0 * CONV5 /
      CONTINUE
      EFU = C(10) # AK / SUMC
      DD 200 I = 10, 17
      EFU = EFU + (C(1) + C(1 + 1)) / 2.0 * CONV5 / SUMC
      CONTINUE
      \mathsf{ETU} = 1.0 - (\mathsf{EBU} + \mathsf{EFU})
    TRACE
      CONTROL 971
      PRINT 25, P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(8),P(9),P(10),
     1P(11),P(12),P(13),P(14),P(15),P(16)
      PUNCH 25, P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(8),P(9),P(10),
     1P(11),P(12),P(13),P(14),P(15),P(16)
      PUNCH 28
      PUNCH 28
      PUNCH 28
      CONTROL 952
      PRINT 300, EFU, ETU, EBU
      PUNCH 300, EFU, ETU, EBU
      FORMAT(9x.6HEFU = .F6.4.13x.6HETU = .F6.4.13x.6HEBU = .F6.4)
      CONTROL 951
      PUNCH 28
      PUNCH 28
      PUNCH 28
      PRINT 320
      PUNCH 320
                  6X,5HANGLE.3X,11HINTENSITY 1,4X,11HINTENSITY 2,4X,
      FORMAT(
     111HINTENSITY 3, 5X, 4HGAIN, 6X, 7HPERCENT)
      PRINT 330
      PUNCH 330
330
      FORMAT(5% 7HDEGREES, 4%, 6HNORMAL, 8%, 8HPARALLEL, 6%;
     111HUNPOLARIZED: 3X: 8HFUNCTIUN: 2X: 12HPDLARIZATION)
      CONTROL 951
      PUNCH 28
      D0 500 I = 1, 18
      D = C(I) * PI / SUMC
      Q = (A(I) - B(I)) / (A(I) + b(I)) * 100.0
      PRINT 400, 1, SS(I), A(I), B(I), C(I), D, Q
      PUNCH 400, 1, SS(1), A(1), B(1), C(1), D. Q
400
      FORMAT(14.1X.F6.1.1X.E13.6.2X.E13.6.2X.E13.6.2X.F7.3.4X.F8.3)
      CONTROL 95%
      PUNCH .28
500
      CONTINUE
      GO TO 20
      END
```

```
Declassified in Part - Sanitized Copy Approved for Release 2012/09/06: CIA-RDP79B00873A001900010120-1
                                     LUMEULNIAL
       PROGRAM MIE COMPRESSOR
                                 PROGRAMMER
                                             BRUCE HERRICK
                                                              ELECTRO-OPTICS X 333
       SET SENSE SWITCH - 01. DOWN FOR MIE-III DATA, UP FOR MIE-S3 DATA
       READ THE VALUE OF M FIRST
       READ TABLE OF ANGLES OF REFRACTION NEXT
       READ DATA BLOCK LAST
       DIMENSION A(10, 37), BL(18), X(3, 10)
       K = 0
       BEGIN PROCEDURE 1
       DO 20 K = 1, M
       READ 16
1.6
       FORMAT(1X)
20
       CONTINUE
       END PROCEDURE 1
22
       READ 23, IM
23
      FORMAT (F6.2)
       CONTROL 971
       PRINT 24. IM
       PUNCH 24, IM
       FORMAT(22X, 31HANGULAR GAIN FUNCTIONS FOR M = 0.066)
       CONTROL 952
       PUNCH 16
       PUNCH 16
       IF (SENSE SWITCH 01) 100, 25
25
       DO 50 I = 1, 10
       M = 4
       EXECUTE PROCEDURE 1
       READ 35, X(1,1)
       FORMAT(43X, F6.4)
       M = 6
       EXECUTE PROCEDURE 1
       DD 50 J = 1, 37
       READ 40, A(1, J)
       FORMAT (57X, F7.3)
       CONTINUE
       PRINT 52
       PUNCH 52
       FORMAT(6X, SHTHETA, 2X, 3HA=1, 4X, 3HA=2, 4X, 3HA=3, 4X, 3HA=4,
      14X, 3HA=5, 4X, 3HA=6, 4X, 3HA=7, 4X, 3HA=8, 4X, 3HA=9, 4X,
      24HA=10)
       CONTROL 951
       PUNCH 16
       DO 80 I = 1. 37
       L = 37 - 1 + 1
       AL = (L - 1) * 5
       AL = 180.0 - AL
                         AL, A(1,L), A(2,L), A(3,L), A(4,L), A(5,L), A(6,L),
       PRINT
              60 · I ·
      1A(7,L),A(8,L),A(9,L),A(10,L)
                         AL a A(1,L) a A(2,L) a A(3,L) a A(4,L) a A(5,L) a A(6,L) a
       PUNCH 60, I.
      1A(7,L),A(8,L),A(9,L),A(10,L)
       FORMAT(14, 1X, F5,0, 1X, F6,2, 1X, F6,2, 1X, F6,2, 1X, F6,2, 1X,
      1F6,2, 1X, F6,2, 1X, F6,2, 1X, F6,2, 1X, F6,2, 1X, F6,2)
       CONTINUE
       CONTROL 971
       PRINT 24° IM
       PUNCH 24, IM
```

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                                     COMPAGENIAL
      CONTROL 952
      PUNCH 16
      PUNCH 16
      PRINT 83
      PUNCH 83
      FORMAT(8X, 1HA, 12X, 3HEFF)
      CONTROL 951
      PUNCH 16
      00 90 I = 1, 10
      PRINT 85, I, X(1,1)
      PUNCH 85, I, X(1,I)
      PUNCH 16
      CONTROL 951
85
      FORMAT(5X, 14, 10X, F6.4)
-0
      CONTINUE
      GD TO 22
100
      IF(K) 101, 101, 109
01
      D0\ 108\ I = 1.18
      READ 105, BL(1)
105
      FORMAT (F5.0)
P08
      CONTINUE
      K = 1
109 %
      DO 120 I = 1, 10
      M = 4
      EXECUTE PROCEDURE 1
      READ 110. X(1, I). X(2,I). X(3,I)
      FORMAT(15X: F6.4, 19X: F6.4, 19X, F6.4)
      EXECUTE PROCEDURE 1
      DC 120 J = 1, 18
      READ 40, A(I, J)
      READ 16
      CONTINUE
      PRINT 52
      PUNCH 52
      CONTROL 951
      PUNCH 16
      DO 150 I = 1, 18
      L = 18 m I + 1
      PRINT 130, I. BL(I), A(1,L), A(2,L), A(3,L), A(4,L), A(5,L), A(6,L),
     1A(7.L),A(8,L),A(9,L),A(10,L)
      PUNCH 130, I. BL(I), A(1.L), A(2.L), A(3.L), A(4.L), A(5.L), A(6.L),
     1A(7,L),A(8,L),A(9,L),A(10,L)
130
      FORMAT(14, 1X, F6,1
                            , F6.2, 1X, F6.2, 1X, F6.2, 1X, F6.2, 1X,
     1F6.2, 1X, F6.2, 1X, F6.2, 1X, F6.2, 1X, F6.2, 1X, F6.2)
      CONTROL 951
      PUNCH 16
      CONTINUE
      CONTROL 971
      PRINT 24, IM
      PUNCH 24, IM
      CONTROL 952
      PUNCH 16
      PUNCH 16
      PRINT 175
      PUNCH 175
      FORMAT(8X, 1HA, 11X, 3HEFU, 13X, 3HETU, 13X, 3HEBU)
```

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CONTROL 951
PUXEH 16
DO 200 I = 1, 10
PRINT 195, I, X(1,1),X(2,1),X(3,1)
PUNCH 195, I, X(1,1),X(2,1),X(3,1)
195
FORMAT(5X, 14, 10X, F6,4, 10X, F6,4, 10X, F6,4)
PUNCH 16
CONTROL 951
CONTINUE
GD TO 22
END
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